
# $18^{th}$ World Hydrogen Energy Conference 2010 – WHEC 2010 Proceedings

## Parallel Sessions Book 5:
- Strategic Analyses
- Safety Issues
- Existing and Emerging Markets

Editors: Detlef Stolten, Thomas Grube

JÜLICH
FORSCHUNGSZENTRUM

Mitglied der Helmholtz-Gemeinschaft

# 18th World Hydrogen Energy Conference 2010 - WHEC 2010: Parallel Sessions Book 5: Strategic Analyses / Safety Issues / Existing and Emerging Markets

WHEC, May 16.-21. 2010, Essen

*Detlef Stolten, Thomas Grube (Eds.)*

Institute of Energy Research - Fuel Cells (IEF-3)

Guide to the Online Edition

Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag

Schriften des Forschungszentrums Jülich / Energy & Environment Vol. 78-5

978-3-89336-655-2 / 1866-1793

# SA Strategic Analyses

## SA.1 Research & Development Targets and Priorities

**Research and Development Targets and Priorities**
*C.A. Trudewind, H.-J. Wagner*
http://hdl.handle.net/2128/4144 3

**Fuzzy AHP/ DEA Approach with Scale Efficiency for Measuring the Relative Efficiency of Hydrogen R&D Programs in the Sector of Developing Hydrogen Energy Technologies**
*S. Lee, J. Kim, G. Mogi, K.S Hui*
http://hdl.handle.net/2128/4145 5

**Introducing Hydrogen as a Future Fuel: Strategies and Activities in Germany**
*O. Ehret, K. Bonhoff*
http://hdl.handle.net/2128/4146 15

**Development Status of Hydrogen and Fuel Cells - Europe**
*W. Tillmetz, U. Bünger*
http://hdl.handle.net/2128/4147 21

**Poster**

## SA.2 Life-Cycle Assessment and Economic Impact

**Life Cycle Analysis and Economic Impact**
*U. Wagner, M. Beer, J. Habermann, P. Pfeifroth*
http://hdl.handle.net/2128/4148 33

**Life Cycle Assessment of Hydrogen Production Processes: Steam Reforming of Natural Gas, Ethanol and Bioethanol**
*J. Dufour, D.P. Serrano, J. Moreno, J.L. Gálvez*
http://hdl.handle.net/2128/4149 35

**Societal Cost-Benefit Analysis of Transportation Options in a Carbon-Constrained World**
*C.E. (Sandy) Thomas*
http://hdl.handle.net/2128/4150 41

**Poster**

**Analysis of Energy Consumption and CO2 Emissions of the Life Cycle of Biohydrogen Applied to the Portuguese Road Transportation Sector**
*A.F. Ferreira, P. Baptista, C. Silva*
http://hdl.handle.net/2128/4151 43

**Extensive Analysis of Hydrogen Costs**
*D.M. Guinea, D. Martín, M.C. García-Alegre, D. Guinea, W.E. Agila*
http://hdl.handle.net/2128/4152 51

**An Exergetic Life Cycle Assessment for Improving Hydrogen Production by Steam Methane Reforming**
*N. Hajjaji, A. Houas, M.N. Pons, V. Ranaudin*
http://hdl.handle.net/2128/4153 59

## SA.3 Socio-Economic Studies

**Strategic and Socioeconomic Studies in Hydrogen Energy**
*D. Hart*
http://hdl.handle.net/2128/4154 65

**Building a Hydrogen Refuelling Infrastructure in the Netherlands: Influencing Factors from the Car Drivers' Perspective**
*I. Bunzeck, J. Backhaus, B. Hoevenaars*
http://hdl.handle.net/2128/4155 67

**The Economic Feasibility of a Sustainable Hydrogen Economy**
*J.J.C. Bruggink, H. Rösler*
http://hdl.handle.net/2128/4156 75

**User Perceptions and Public Attitudes towards Hydrogen Fuel Cell Fleet Vehicles in the EU**
*K. Pietzner, N. Morgunova, M. Yetano, P. Viebahn*
http://hdl.handle.net/2128/4157 83

**How to Improve the Public Perception of Hydrogen?**
*C. Bouallou, J. de Castro, F. Werkoff*
http://hdl.handle.net/2128/4158 89

**Poster**

**Fuel Cell and Hydrogen (FCH2) Technology Creates Business Opportunities beyond Products and Applications**
*M. Corneille, A. Huss*
http://hdl.handle.net/2128/4159 93

**Lessons for Low-Power Fuel Cell Vehicles from a Demonstration Project: Results of Techno-Economic, Safety, Environmental and Social Assessment of the EUHYCHAIN MINI-TRANS Project**
*P. Viebahn, K. Pietzner, A. Laurent, Y. Lechon*
http://hdl.handle.net/2128/4160 97

## SA.4 Education and Public Awareness

**Education and Public Awareness**
*T.I. Sigfusson, B. Emonts*
http://hdl.handle.net/2128/4161 105

**Role of Hydrogen on Engineering Education: ICHET Example**
*M. Suha Yazici*
http://hdl.handle.net/2128/4162 107

**Contributions to Training and Education Made by Institutional Research**
*B. Emonts, D. Stolten*
http://hdl.handle.net/2128/4163 115

**Market Introduction of Hydrogen Technology: the Evolution of the Global Education and Vocational Training Markets**
*A. Johnsen, U. Kueter*
http://hdl.handle.net/2128/4164 123

**New Hydrogen Outreach Program for Education (New HOPE): an American Case Study**
*M.-R. de Valladares*
http://hdl.handle.net/2128/4165 129

**Understanding the Public Acceptance of Hydrogen Technologies in Transport: a Conceptual Framework**
*N. Huijts, E. Molin, L. Steg*
http://hdl.handle.net/2128/4166 137

**Acceptance of Hydrogen Technologies and the Role of Trust**
*R. Zimmer, N. Hölzinger*
http://hdl.handle.net/2128/4167 143

**Poster**

**Light Mobility Applications towards Public Education and Research**
*Y. Ceviz, M. Eroglu, T. Akfidan, S. Altinel, M. S. Yazici*
http://hdl.handle.net/2128/4168 149

**Mobile Renewable House**
*M.F. Serincan, M. Eroglu, M.S. Yazici*
http://hdl.handle.net/2128/4169 157

## SA.5 Market Introduction

**Market Introduction for Hydrogen and Fuel Cell Technologies**
*M. Haug, H.-J. Neef*
http://hdl.handle.net/2128/4170 165

**Overview and Status Quo of the NextHyLights Project**
*U. Buenger, E. Ramschak, B. Madden, I. Bunzeck*
http://hdl.handle.net/2128/4171 167

**Hydrogen at Wastewater Treatment Plants – Optimal Conditions for the Start-Up of a New System**
*M. Schröder, F.-W. Bolle, S. Gredigk-Hoffmann, H. Riße*
http://hdl.handle.net/2128/4172 175

**Hydrogen Rickshaws Fleet Demonstration in New Delhi**
*F. Villatico, L. M. Das, M. Abraham, I. Willianson*
http://hdl.handle.net/2128/4173 179

**Poster**

**Horizon Hydrogène Energie : 19 Partners for Breakthrough Innovations on Early Markets**
*M. Julien, L. Allidiere*
http://hdl.handle.net/2128/4174 185

**Strategies for the Commercial Introduction of Modular Low Power Fuel Cells**
*P.E. de Miranda, A. Laufer, H.V. de Miranda*
http://hdl.handle.net/2128/4175 189

**HCNG – A Dead End or a Bridge to the Future?**
*C. Nelsson, C. Hulteberg, J. Saint-Just, M. Kaiadi*
http://hdl.handle.net/2128/4176 195

## SA.7 Regional Activities

**Hydrogen and Fuel Cells around the Corner – the Role of Regions and Municipalities Towards Commercialization**
*A. Ziolek, M. Reijalt, T. Kattenstein*
http://hdl.handle.net/2128/4177 205

**Platform for Promoting a Hydrogen Economy in Southwest Europe: the HYRREG Project**
*R. Fernandes, C. Gonzalo, J.M. García, E. Chacón*
http://hdl.handle.net/2128/4178 207

**HYCHAIN: Assessment of the Development and Deployment of Several Fleets of Small Hydrogen Powered Hybrid Vehicles**
*M. Dupont, P. Paulmier*
http://hdl.handle.net/2128/4179 213

**Collaboration in a Local Hydrogen Cluster in Germany**
*B. Jermer*
http://hdl.handle.net/2128/4180 219

### Poster

**The HyRREG Project: A Roadmap for SUDOE**
*E. Chacón, L. Pazos, R. Fernandes, R. Pimenta*
http://hdl.handle.net/2128/4181 223

## SA.8 The Zero Regio Project

**Zero Regio: Recent Experience with Hydrogen Vehicles and Re-fueling Infrastructure**
*H. Lienkamp, A. Rastogi*
http://hdl.handle.net/2128/4182 231

## Poster

# SI Safety Issues

## SI.1 Vehicle and Infrastructural Safety

**Safety Analysis of Hydrogen Vehicles and Infrastructure**
*T. Jordan, W. Breitung*
http://hdl.handle.net/2128/4183 235

**Safety Distances for Hydrogen Refuelling Station**
*A. Engebø, F. Barth, F. Markert, P. Middha, M. Wardman, J. Chaineaux, D. Sebarnescu, D. Baraldi, S. Nilsen, A.V. Tchouvelev, N. Versloot, A. Marangon*
http://hdl.handle.net/2128/4184 237

**Speaking of Safety: Learning from Safety Reviews**
*S.C. Weiner, R.A. Kallman, E.G. Skolnik*
http://hdl.handle.net/2128/4185 243

**Safety Aspects of Hydrogen Fuel Cell Vehicles**
*C. Sachs, A. Mack-Gardner*
http://hdl.handle.net/2128/4186 249

**Study on the Fire Response of Vehicles with Compressed Hydrogen Cylinders**
*Y. Tamura, J. Tomioka, J. Suzuki*
http://hdl.handle.net/2128/4187 253

**Damage Detection in High-Pressure Storage Cylinders**
*M. Sulatisky, D. Mourre, D.R. Hay*
http://hdl.handle.net/2128/4188 261

**Self Ignition of Hydrogen by Various Mechanisms**
*M. Royle, J. Gummer, P. Hooker, D. Willoughby, J. Udensi*
http://hdl.handle.net/2128/4189 267

**Simulation of Hydrogen Releases from Fuel-Cell Vehicles in Tunnels**
*W.G. Houf, G.H. Evans, S.C. James, E. Merilo, M. Groethe*
http://hdl.handle.net/2128/4190 275

**Hydrogen Safety: R&D Work in the Horizon Hydrogen Energie Program**
*S. Ruban, S. Jallais, D. Houssin, V. Naudet, C. Weber, J. Daubech, C. Proust, A. Bengaouer*
http://hdl.handle.net/2128/4191 283

**Selecting Hydrogen Embrittlement Resistant Materials by Means of the Disc Rupture Test**
*E. Leunis, L. Duprez*
http://hdl.handle.net/2128/4192 289

**Poster**

**GASTEF: The JRC-IE Compressed Hydrogen Gas Tanks Testing Facility**
*B. Acosta, P. Moretto, N. Frischauf, F. Harskamp*
http://hdl.handle.net/2128/4193 295

**Performance Testing of a MOSFET Sensor**
*G. Black, L. Brett, P. Moretto, J. Bousek*
http://hdl.handle.net/2128/4194 301

**Smart Fibre Optic Methods for Structural Health Monitoring of High Pressure Vessels for Hydrogen Storage**
*P. Gąsior, W. Błażejewski, J. Kaleta*
http://hdl.handle.net/2128/4195 309

**AppliedSensor FE Hydrogen Sensor**
*M. Kosovic, N. Edvardsson*
http://hdl.handle.net/2128/4196 315

**Risk Associated with the Use of Barriers in Hydrogen Refueling Stations**
*J. LaChance, J. Phillips, W. Houf*
http://hdl.handle.net/2128/4197 323

## SI.2 Regulations, Codes, Standards and Test Methods

**Advancing Commercialization of Hydrogen and Fuel Cell Technologies Through International Cooperation of Regulations, Codes, and Standards (RCS)**
*R. Dey*
http://hdl.handle.net/2128/4198 333

**Regulations, Codes & Standards for the Approval of Hydrogen Refuelling Stations**
*R. Wurster, G.P. Haugom, T. Elliger*
http://hdl.handle.net/2128/4199 335

**Methods for Response and Recovery Time Measurement of Hydrogen Sensors**
*G. Black, L. Bret, P. Moretto, J. Bousek*
http://hdl.handle.net/2128/4200 339

### Poster

**H2 Ignition by Hot Surfaces: Safety Issues and Test Methods**
*C. Morreale, S. Marengo, G. Migliavacca, A. Maggioni*
http://hdl.handle.net/2128/4201 345

# SM Existing and Emerging Markets

## SM.1 Off-Grid Power Supply and Premium Power Generation

**Sizing of Photovoltaic System Coupled with Hydrogen Storage Based on the ORIENTE Model**
*C. Thibault, C. Darras, M. Muselli, P. Poggi*
http://hdl.handle.net/2128/4202 353

**Tool for Optimal Design and Operation of Hydrogen Storage Based Autonomous Energy Systems**
*B. Oberschachtsiek, D. Lemken, M. Stark, G. Krost*
http://hdl.handle.net/2128/4203 359

**Backup Power Fuel Cell Systems for Telecom Applications**
*R. Romer*
http://hdl.handle.net/2128/4204 369

**Poster**

**250 Wel Reformer Fuel Cell System for Bio-Ethanol**
*T. Aicher, J. Full, G. Kraaij*
http://hdl.handle.net/2128/4205 375

**Solar-hydrogen Based Autonomous Electric Power System in Operation**
*M. Brinkhaus, D. Jarosch, J. Kapischke*
http://hdl.handle.net/2128/4206 379

**Remote Telecom System Including Photovoltaic Energy and H2 Production by Electrolysis**
*E. Chacón, R. Cuevas, G. Martínez, G. Gómez*
http://hdl.handle.net/2128/4207 385

**Fuel Cells as Back-up DC Power Supply for Substations**
*M. Hölscher, G. Bittner, P. Rümenapp*
http://hdl.handle.net/2128/4208 391

**Off-Grid Energy Systems with Fuel Cell Technology: A Challenge for Technical Training**
*K. Rupprecht, K. Frank*
http://hdl.handle.net/2128/4209 395

## SM.2 Space and Aeronautic Applications

**Aerospace Applications of Hydrogen and Fuel Cells**
*C. Roessler, J. Schoemann, H. Baier*
http://hdl.handle.net/2128/4210 401

**Innovative Hydrogen Storage Solutions for Aerospace Applications**
*M. Keding, A. Reissner, G. Schmid, M. Tajmar*
http://hdl.handle.net/2128/4211 403

**Desulfurization of Jet Fuel for Fuel Cell-based APU Systems in Aircraft**
*Y. Wang, J. Pasel, R. Peters, D. Stolten*
http://hdl.handle.net/2128/4212 409

### Poster

**Unmanned Aerial Vehicle Driven by Fuel Cell Technology, AVIZOR**
*E. Chacón, G. Martínez, C. Anchuelo, R. Cuevas*
http://hdl.handle.net/2128/4213 417

**Airport Liquid Hydrogen Infrastructure for Aircraft Auxiliary Power Units**
*C. Stiller, P. Schmidt*
http://hdl.handle.net/2128/4214 423

## SM.3 APUs for Road Vehicles, Ships and Airplanes

**Auxiliary Power Units for Light-Duty Vehicles, Trucks, Ships, and Airplanes**
*R. Peters*
http://hdl.handle.net/2128/4215 433

**Fuel Cell System Development and Testing for Aircraft Applications**
*J. Kallo, G. Renouard-Vallet, M. Saballus, G. Schmithals, J. Schirmer, K.A. Friedrich*
http://hdl.handle.net/2128/4216 435

**New Developments for Maritime Fuel Cell Systems**
*F. Vogler, G. Würsig*
http://hdl.handle.net/2128/4217 445

**Bio-methanol Fuel Cell Systems for Ships**
*P. van den Oosterkamp, A.-M. Tjeerdsma, M. Couwenberg*
http://hdl.handle.net/2128/4218 455

**Development of an Ultra Compact CPOX Reactor for Diesel Fuel**
*G. Motohashi, H. Mikami, J. Iwamoto, S. Roychoudhury*
http://hdl.handle.net/2128/4219 463

**Development Progress of Small Fuel Cell Systems for Future Vehicles**
*M. Bauer, G. Götz, W. Strobl*
http://hdl.handle.net/2128/4220 471

### Poster

**An Approach to the Precise Dosing of Fluids**
*A. Müller, M. Gunkel, H. Kappler, T. Rolland*
http://hdl.handle.net/2128/4221 479

## SM.4 Portable Applications and Light Traction

**Portable Applications and Light Traction**
*J. Garche*
http://hdl.handle.net/2128/4222 487

**A Fuel Cell Driven Aircraft Baggage Tractor**
*S. van Sterkenburg, A. van Rijs, H. Hupkens*
http://hdl.handle.net/2128/4223 489

**System Technology Aspects for Light Traction Applications of Direct Methanol Fuel Cells**
*H. Janßen, L. Blum, M. Hehemann, J. Mergel, D. Stolten*
http://hdl.handle.net/2128/4224 497

**Development of a 100W PEM Fuel Cell Stack for Portable Applications**
*I. Eroglu, S. Erkan*
http://hdl.handle.net/2128/4225 503

### Poster

**Sub Kilowatt Fuel Cell Systems – Solutions for Applications**
*P. Beckhaus, S. Gößling, T. Notthoff, A. Heinzel*
http://hdl.handle.net/2128/4226 509

**Recent Development of Portable DMFC Influenced by Simplo-ITRI Cooperation**
*W. Ling, L. Tsai, C.-C. Lai, M.-H. Wang*
http://hdl.handle.net/2128/4227 517

**Hybridization and Control of Direct Methanol Fuel Cell Systems for Material Handling Applications**
*J. Wilhelm, L. Blum, H. Janßen, J. Mergel, D. Stolten*
http://hdl.handle.net/2128/4228 523

Schriften des Forschungszentrums Jülich
Energy & Environment Volume 78-5

Forschungszentrum Jülich GmbH
Institute of Energy Research (IEF)
Fuel Cells (IEF-3)

# 18th World Hydrogen Energy Conference 2010 – WHEC 2010

## Parallel Sessions Book 5:
## - Strategic Analyses
## - Safety Issues
## - Existing and Emerging Markets

Editors: Detlef Stolten, Thomas Grube

Schriften des Forschungszentrums Jülich
Energy & Environment Volume 78-5

ISSN 1866-1793 ISBN 978-3-89336-655-2

Bibliographic information published by the Deutsche Nationalbibliothek.
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Vol. 78 Set (komplett)
ISBN 978-3-89336-657-6
Editors: Detlef Stolten, Thomas Grube, Bernd Emonts

| | |
|---|---|
| Publisher and Distributor: | Forschungszentrum Jülich GmbH<br>Zentralbibliothek<br>52425 Jülich<br>Phone +49 (0) 24 61 61-53 68 · Fax +49 (0) 24 61 61-61 03<br>e-mail: zb-publikation@fz-juelich.de<br>Internet: http://www.fz-juelich.de/zb |
| Cover Design: | Grafische Medien, Forschungszentrum Jülich GmbH |
| Printer: | Grafische Medien, Forschungszentrum Jülich GmbH |
| Copyright: | Forschungszentrum Jülich 2010 |

Schriften des Forschungszentrums Jülich
Reihe Energy & Environment Volume 78-5

ISSN 1866-1793
ISBN 978-3-89336-655-2

The complete volume ist freely available on the Internet on the Jülicher Open Access Server (JUWEL) at http://www.fz-juelich.de/zb/juwel

# Book 5: Strategic Analyses | Safety Issues | Existing and Emerging Markets

## Contents


## SA STRATEGIC ANALYSES

**SA.1 Research & Development Targets and Priorities 1**

Research and Development Targets and Priorities
*C.A. Trudewind, H.-J. Wagner* 3

Fuzzy AHP/ DEA Approach with Scale Efficiency for Measuring the Relative Efficiency of Hydrogen R&D Programs in the Sector of Developing Hydrogen Energy Technologies
*S. Lee, J. Kim, G. Mogi, K.S Hui* 5

Introducing Hydrogen as a Future Fuel: Strategies and Activities in Germany
*O. Ehret, K. Bonhoff* 15

Development Status of Hydrogen and Fuel Cells - Europe
*W. Tillmetz, U. Bünger* 21

**SA.2 Life-Cycle Assessment and Economic Impact 31**

Life Cycle Analysis and Economic Impact
*U. Wagner, M. Beer, J. Habermann, P. Pfeifroth* 33

Life Cycle Assessment of Hydrogen Production Processes: Steam Reforming of Natural Gas, Ethanol and Bioethanol
*J. Dufour, D.P. Serrano, J. Moreno, J.L. Gálvez* 35

Societal Cost-Benefit Analysis of Transportation Options in a Carbon-Constrained World
*C.E. (Sandy) Thomas* 41

**Posters**

Analysis of Energy Consumption and $CO_2$ Emissions of the Life Cycle of Bio-hydrogen Applied to the Portuguese Road Transportation Sector
*A.F. Ferreira, P. Baptista, C. Silva* 43

Extensive Analysis of Hydrogen Costs
*D.M. Guinea, D. Martín, M.C. García-Alegre, D. Guinea, W.E. Agila* 51

An Exergetic Life Cycle Assessment for Improving Hydrogen Production by Steam Methane Reforming
*N. Hajjaji, A. Houas, M.N. Pons, V. Ranaudin* 59

**SA.3 Socio-Economic Studies** **63**

Strategic and Socioeconomic Studies in Hydrogen Energy
*D. Hart* *65*

Building a Hydrogen Refuelling Infrastructure in the Netherlands: Influencing Factors from the Car Drivers' Perspective
*I. Bunzeck, J. Backhaus, B. Hoevenaars* *67*

The Economic Feasibility of a Sustainable Hydrogen Economy
*J.J.C. Bruggink, H. Rösler* *75*

User Perceptions and Public Attitudes towards Hydrogen Fuel Cell Fleet Vehicles in the EU
*K. Pietzner, N. Morgunova, M. Yetano, P. Viebahn* *83*

How to Improve the Public Perception of Hydrogen?
*C. Bouallou, J. de Castro, F. Werkoff* *89*

**Posters**

Fuel Cell and Hydrogen (FCH2) Technology Creates Business Opportunities beyond Products and Applications
*M. Corneille, A. Huss* *93*

Lessons for Low-Power Fuel Cell Vehicles from a Demonstration Project: Results of Techno-Economic, Safety, Environmental and Social Assessment of the EU-HYCHAIN MINI-TRANS Project
*P. Viebahn, K. Pietzner, A. Laurent, Y. Lechon* *97*

**SA.4 Education and Public Awareness** **103**

Education and Public Awareness
*T.I. Sigfusson, B. Emonts* *105*

Role of Hydrogen on Engineering Education: ICHET Example
*M. Suha Yazici* *107*

Contributions to Training and Education Made by Institutional Research
*B. Emonts, D. Stolten* *115*

Market Introduction of Hydrogen Technology: the Evolution of the Global Education and Vocational Training Markets
*A. Johnsen, U. Kueter* *123*

New Hydrogen Outreach Program for Education (New HOPE): an American Case Study
*M.-R. de Valladares* *129*

Understanding the Public Acceptance of Hydrogen Technologies in Transport: a Conceptual Framework
*N. Huijts, E. Molin, L. Steg* *137*

Acceptance of Hydrogen Technologies and the Role of Trust
*R. Zimmer, N. Hölzinger* *143*

**Posters**

Light Mobility Applications towards Public Education and Research
*Y. Ceviz, M. Eroglu, T. Akfidan, S. Altinel, M. S. Yazici* 149

Mobile Renewable House
*M.F. Serincan, M. Eroglu, M.S. Yazici* 157

**SA.5 Market Introduction 163**

Market Introduction for Hydrogen and Fuel Cell Technologies
*M. Haug, H.-J. Neef* 165

Overview and Status Quo of the NextHyLights Project
*U. Buenger, E. Ramschak, B. Madden, I. Bunzeck* 167

Hydrogen at Wastewater Treatment Plants – Optimal Conditions for the Start-Up of a New System
*M. Schröder, F.-W. Bolle, S. Gredigk-Hoffmann, H. Riße* 175

Hydrogen Rickshaws Fleet Demonstration in New Delhi
*F. Villatico, L. M. Das, M. Abraham, I. Willianson* 179

**Posters**

Horizon Hydrogène Energie : 19 Partners for Breakthrough Innovations on Early Markets
*M. Julien, L. Allidiere* 185

Strategies for the Commercial Introduction of Modular Low Power Fuel Cells
*P.E. de Miranda, A. Laufer, H.V. de Miranda* 189

HCNG – A Dead End or a Bridge to the Future?
*C. Nelsson, C. Hulteberg, J. Saint-Just, M. Kaiadi* 195

**SA.7 Regional Activities 203**

Hydrogen and Fuel Cells around the Corner – the Role of Regions and Municipalities Towards Commercialization
*A. Ziolek, M. Reijalt, T. Kattenstein* 205

Platform for Promoting a Hydrogen Economy in Southwest Europe: the HYRREG Project
*R. Fernandes, C. Gonzalo, J.M. García, E. Chacón* 207

HYCHAIN: Assessment of the Development and Deployment of Several Fleets of Small Hydrogen Powered Hybrid Vehicles
*M. Dupont, P. Paulmier* 213

Collaboration in a Local Hydrogen Cluster in Germany
*B. Jermer* 219

**Poster**

The HyRREG Project: A Roadmap for SUDOE
*E. Chacón, L. Pazos, R. Fernandes, R. Pimenta* 223

**SA.8 The Zero Regio Project 229**

Zero Regio: Recent Experience with Hydrogen Vehicles and Refueling Infrastructure
*H. Lienkamp, A. Rastogi* 231

**SI SAFETY ISSUES**

**SI.1 Vehicle and Infrastructural Safety 233**

Safety Analysis of Hydrogen Vehicles and Infrastructure
*T. Jordan, W. Breitung* 235

Safety Distances for Hydrogen Refuelling Station
*A. Engebø, F. Barth, F. Markert, P. Middha, M. Wardman, J. Chaineaux, D. Sebarnescu, D. Baraldi, S. Nilsen, A.V. Tchouvelev, N. Versloot, A. Marangon* 237

Speaking of Safety: Learning from Safety Reviews
*S.C. Weiner, R.A. Kallman, E.G. Skolnik* 243

Safety Aspects of Hydrogen Fuel Cell Vehicles
*C. Sachs, A. Mack-Gardner* 249

Study on the Fire Response of Vehicles with Compressed Hydrogen Cylinders
*Y. Tamura, J. Tomioka, J. Suzuki* 253

Damage Detection in High-Pressure Storage Cylinders
*M. Sulatisky, D. Mourre, D.R. Hay* 261

Self Ignition of Hydrogen by Various Mechanisms
*M. Royle, J. Gummer, P. Hooker, D. Willoughby, J. Udensi* 267

Simulation of Hydrogen Releases from Fuel-Cell Vehicles in Tunnels
*W.G. Houf, G.H. Evans, S.C. James, E. Merilo, M. Groethe* 275

Hydrogen Safety: R&D Work in the Horizon Hydrogen Energie Program
*S. Ruban, S. Jallais, D. Houssin, V. Naudet, C. Weber, J. Daubech, C. Proust, A. Bengaouer* 283

Selecting Hydrogen Embrittlement Resistant Materials by Means of the Disc Rupture Test
*E. Leunis, L. Duprez* 289

**Posters**

GASTEF: The JRC-IE Compressed Hydrogen Gas Tanks Testing Facility
*B. Acosta, P. Moretto, N. Frischauf, F. Harskamp* 295

Performance Testing of a MOSFET Sensor
*G. Black, L. Brett, P. Moretto, J. Bousek* 301

Smart Fibre Optic Methods for Structural Health Monitoring of High Pressure Vessels for Hydrogen Storage
*P. Gąsior, W. Błażejewski, J. Kaleta* 309

AppliedSensor FE Hydrogen Sensor
*M. Kosovic, N. Edvardsson* 315

Risk Associated with the Use of Barriers in Hydrogen Refueling Stations
*J. LaChance, J. Phillips, W. Houf* 323

**SI.2 Regulations, Codes, Standards and Test Methods 331**

Advancing Commercialization of Hydrogen and Fuel Cell Technologies Through International Cooperation of Regulations, Codes, and Standards (RCS)
*R. Dey* 333

Regulations, Codes & Standards for the Approval of Hydrogen Refuelling Stations
*R. Wurster, G.P. Haugom, T. Elliger* 335

Methods for Response and Recovery Time Measurement of Hydrogen Sensors
*G. Black, L. Bret, P. Moretto, J. Bousek* 339

**Poster**

$H_2$ Ignition by Hot Surfaces: Safety Issues and Test Methods
*C. Morreale, S. Marengo, G. Migliavacca, A. Maggioni* 345

**SM EXISTING AND EMERGING MARKETS**

**SM.1 Off-Grid Power Supply and Premium Power Generation 351**

Sizing of Photovoltaic System Coupled with Hydrogen Storage Based on the ORIENTE Model
*C. Thibault, C. Darras, M. Muselli, P. Poggi* 353

Tool for Optimal Design and Operation of Hydrogen Storage Based Autonomous Energy Systems
*B. Oberschachtsiek, D. Lemken, M. Stark, G. Krost* 359

Backup Power Fuel Cell Systems for Telecom Applications
*R. Romer* 369

**Posters**

250 Wel Reformer Fuel Cell System for Bio-Ethanol
*T. Aicher, J. Full, G. Kraaij* 375

Solar-hydrogen Based Autonomous Electric Power System in Operation
*M. Brinkhaus, D. Jarosch, J. Kapischke* 379

Remote Telecom System Including Photovoltaic Energy and $H_2$ Production by Electrolysis
*E. Chacón, R. Cuevas, G. Martínez, G. Gómez* 385

Fuel Cells as Back-up DC Power Supply for Substations
*M. Hölscher, G. Bittner, P. Rümenapp* 391

Off-Grid Energy Systems with Fuel Cell Technology: A Challenge for Technical Training
*K. Rupprecht, K. Frank* *395*

**SM.2 Space and Aeronautic Applications 399**

Aerospace Applications of Hydrogen and Fuel Cells
*C. Roessler, J. Schoemann, H. Baier* *401*

Innovative Hydrogen Storage Solutions for Aerospace Applications
*M. Keding, A. Reissner, G. Schmid, M. Tajmar* *403*

Desulfurization of Jet Fuel for Fuel Cell-based APU Systems in Aircraft
*Y. Wang, J. Pasel, R. Peters, D. Stolten* *409*

**Posters**

Unmanned Aerial Vehicle Driven by Fuel Cell Technology, AVIZOR
*E. Chacón, G. Martínez, C. Anchuelo, R. Cuevas* *417*

Airport Liquid Hydrogen Infrastructure for Aircraft Auxiliary Power Units
*C. Stiller, P. Schmidt* *423*

**SM.3 APUs for Road Vehicles, Ships and Airplanes 431**

Auxiliary Power Units for Light-Duty Vehicles, Trucks, Ships, and Airplanes
*R. Peters* *433*

Fuel Cell System Development and Testing for Aircraft Applications
*J. Kallo, G. Renouard-Vallet, M. Saballus, G. Schmithals, J. Schirmer, K.A. Friedrich* *435*

New Developments for Maritime Fuel Cell Systems
*F. Vogler, G. Würsig* *445*

Bio-methanol Fuel Cell Systems for Ships
*P. van den Oosterkamp, A.-M. Tjeerdsma, M. Couwenberg* *455*

Development of an Ultra Compact CPOX Reactor for Diesel Fuel
*G. Motohashi, H. Mikami, J. Iwamoto, S. Roychoudhury* *463*

Development Progress of Small Fuel Cell Systems for Future Vehicles
*M. Bauer, G. Götz, W. Strobl* *471*

**Poster**

An Approach to the Precise Dosing of Fluids
*A. Müller, M. Gunkel, H. Kappler, T. Rolland* *479*

**SM.4 Portable Applications and Light Traction 485**

Portable Applications and Light Traction
*J. Garche* *487*

A Fuel Cell Driven Aircraft Baggage Tractor
*S. van Sterkenburg, A. van Rijs, H. Hupkens* *489*

System Technology Aspects for Light Traction Applications of Direct Methanol Fuel Cells
*H. Janßen, L. Blum, M. Hehemann, J. Mergel, D. Stolten* 497

Development of a 100W PEM Fuel Cell Stack for Portable Applications
*I. Eroglu, S. Erkan* 503

**Posters**

Sub Kilowatt Fuel Cell Systems – Solutions for Applications
*P. Beckhaus, S. Gößling, T. Notthoff, A. Heinzel* 509

Recent Development of Portable DMFC Influenced by Simplo-ITRI Cooperation
*W. Ling, L. Tsai, C.-C. Lai, M.-H. Wang* 517

Hybridization and Control of Direct Methanol Fuel Cell Systems for Material Handling Applications
*J. Wilhelm, L. Blum, H. Janßen, J. Mergel, D. Stolten* 523

# SA Strategic Analyses

SA.1 Research & Development Targets and Priorities
SA.2 Life-Cycle Assessment and Economic Impact
SA.3 Socio-Economic Studies
SA.4 Education and Public Awareness
SA.5 Market Introduction
SA.7 Regional Activities
SA.8 The Zero Regio Project

# Research and Development Targets and Priorities

Clemens Alexander Trudewind and Hermann-Josef Wagner

**Abstract**

Coming from the state of energy distribution and conversion technologies there are many alternatives for transforming the energy system to a hydrogen economy. Many techniques could be introduced for the same purpose but level of development and benefit differ from time to time. Therefore the paper highlights targets of a sustainable energy system, political frameworks, scenarios of infrastructural developments and the state of the art for several hydrogen technologies. The most relevant research fields which were identified concern the reduction of expenses for efficient catalysis by reducing material inputs as well as manufacturing costs of fuel cells and the development of large scale (HT-)electrolysis for adapting to regenerative electricity.

# Fuzzy AHP/ DEA Approach with Scale Efficiency for Measuring the Relative Efficiency of Hydrogen R&D Programs in the Sector of Developing Hydrogen Energy Technologies

**Seongkon Lee**, **Jongwook Kim**, Energy Policy Research Center, Korea Institute of Energy Research, Republic of Korea
**Gento Mogi**, Technology Management for Innovation, Graduate school of Engineering, The Univ. of Tokyo, Japan
**K.S Hui**, Manufacturing engineering and engineering management, City Univ. of Hong Kong, Hong Kong

## 1 Introduction

Korea takes 10th place of largest energy consuming nations in the world since she spends 222 million ton of oil equivalent per year and depends on the most amount of consumed energy resources, which account for 96% import in 2008 with the 5.6% self-sufficiency ratio of energy resources. The interest of energy technology development has increased due to her poor energy environments. Specifically, the fluctuation of oil prices has been easily affecting Korean energy environments and economy. Considering her energy environments, energy technology development can be one of the optimal solution and breakthrough to solve Korea's energy circumstances, energy security, and the low carbon green growth with Korea's sustainable development. Moreover, energy and environment issues are the key factors for leading the future sustainable competitive advantage and green growth of one nation over the others nations. Lots of advanced nations have been trying to develop the energy technologies with the establishment of the strategic energy technology R&D programs for creating and maintain a competitive advantage and leading the global energy market.

In 2005, we established strategic hydrogen energy technology roadmap in the sector of developing hydrogen energy technologies for coping with next 10 years from 2006 to 2015 as an aspect of hydrogen energy technology development. Hydrogen energy technologies are environmentally sound and friendly comparing with conventional energy technologies. Hydrogen energy technologies can play a key role and is the one of the best alternatives getting much attentions coping with UNFCCC and the hydrogen economy. Hydrogen energy technology roadmap shows meaningful guidelines for implementing the low carbon green growth society.

We analyzed the world energy outlook to make hydrogen ETRM and provide energy policy directions in 2005. It focuses on developing hydrogen energy technology considering Korea's energy circumstance. We make a list of evaluation criteria for assessing and prioritize hydrogen energy technologies in the sector of hydrogen ETRM with finite resources and R&D funds. The criteria are composed of economic impact, commercial potential, inner capacity, and technical spin-off. Hydrogen ETRM supplies primary energy technologies to be developed with a long-term view for the low carbon green growth. We suggest Korea's long-term direction and strategy for developing hydrogen energy technologies in the sector of hydrogen ETRM with the hydrogen economy. The main purpose of this research is to assess the priority of hydrogen energy technologies in the sector of hydrogen ETRM since we allocate and invest R&D budgets strategically as an extended research [1]. In this paper, we focus on the assessment of hydrogen energy technologies econometrically by using an integrated 2-stage approach, which is fuzzy analytic hierarchy (Fuzzy AHP) process and the data envelopment analysis (DEA) in the sector of hydrogen energy technologies. The research results suggest the most efficient hydrogen energy technology is selected by the multi-criteria decision making approach. In addition it also provides Korean hydrogen energy technology policymakers and decision makers with the right hydrogen energy technologies econometrically as they implement a strategic R&D plan.

## 2 Fuzzy Sets and Numbers

In the real world, it is not easy to extract precise data concerning measurement indicators. And decision makers prefer natural language expression rather than crisp numbers in assessment of decision making problems. Fuzzy set theory deals with ambiguous situations effectively with the interval values instead of crisp numbers. It looks like human thoughts and perceptions of using approximate information and uncertainty to generate the reasonable alternative of decision making problem. The concept of fuzzy theory was introduced by Zadeh in 1965 [2]. Fuzzy theory includes fuzzy set, membership function, and fuzzy number to change vague data into useful data efficiently. Fuzzy set theory implements groups of data with boundaries that are not sharply defined. The merit of using fuzzy approach is to express the relative importance of the alternatives and the criteria with fuzzy numbers instead of using crisp numbers because most of the decision making in the real world takes place in a situation where the pertinent data and the sequences of possible actions are not precisely known. Triangular and trapezoidal fuzzy numbers are usually used to capture the vagueness of the parameters related to select the alternatives. TFN is expressed with boundaries instead of crisp numbers for reflecting the fuzziness as decision makers select the alternatives or pair-wise comparisons matrix. In this research, we use triangular fuzzy numbers (TFN) to prioritize hydrogen energy technology in the sector of hydrogen ETRM with fuzziness. TFN is designated as $M_{ij} = (l_{ij}, m_{ij}, u_{ij})$. $m_{ij}$ is the median value of fuzzy number $M_{ij}$. $l_{ij}$ and $u_{ij}$ is the left and right side of fuzzy number $M_{ij}$ respectively.

Consider two TFN $M_1$ and $M_2$, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$. Their operations laws are as follows:

$$(l_1,m_1,u_1)\oplus(l_2,m_2,u_2)=(l_1+l_2,m_1+m_2,u_1+u_2) \tag{1}$$

$$(l_1,m_1,u_1)\otimes(l_2,m_2,u_2)=(l_1\times l_2,m_1\times m_2,u_1\times u_2) \tag{2}$$

$$(l_1,m_1,u_1)^{-1}=(1/u_1,1/m_1,1/l_1) \tag{3}$$

## 3 Fuzzy AHP

The analytic hierarchy process (AHP) is a subjective method for analyzing qualitative criteria to weight the alternatives. Saaty suggested AHP as a decision making tool to resolve unstructured problems since 1977 [3]. Generally, decision making involves various areas such as planning, selecting a best policy, the competitiveness analysis [4], and allocating resources efficiently. In this research, though the AHP is able to capture the expert's knowledge by perception or preference, the AHP still cannot reflect the human thoughts totally with crisp numbers. Therefore, fuzzy AHP, which is a fuzzy extension of AHP, is applied to solve the hierarchical fuzzy decision making problems with fuzzy scales instead of crisp numbers. Fuzzy AHP is also applied to the real world decision making problem such as implementation of the optimal R&D policy, R&D plan and resource allocation widely [5].

We use the fuzzy scale when decision makers make pairwise comparisons.

Let $A = (a_{ij})_{nxm}$ be a fuzzy pairwise comparison judgements matrix. Let $M_{ji} = (l_{ij}, m_{ij}, u_{ij})$ be a TFN.

The procedure of fuzzy AHP is as follows:

Step 1: We make pairwise comparisons of attributes by using the fuzzy numbers in the same level of hierarchy structure.

Step 2: The value of fuzzy synthetic extent with respect to the i[th] object is defined as

$$S_i = \sum_{j=1}^{m} M_{ij} \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right]^{-1} \tag{4}$$

s.t $$\sum_{j=1}^{m} M_{ij} = \left( \sum_{j=1}^{m} l_{ij}, \sum_{j=1}^{m} m_{ij}, \sum_{j=1}^{m} u_{ij} \right), \quad i = 1, 2, 3, \ldots, n \tag{5}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} = \left( \sum_{i=1}^{n} \sum_{j=1}^{m} l_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} m_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} u_{ij} \right) \tag{6}$$

$$\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right]^{-1} = \left( \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} u_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} m_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} l_{ij}} \right) \tag{7}$$

We calculate TFN value of Si=( $l_i$, $m_i$, $u_i$) by the formula (4), (5), (6), and (7).

Step 3: We compare the values of $S_i$ respectively and calculate the degree of possibility of $S_j=(l_j, m_j, u_j) \geq S_i=(l_i, m_i, u_i)$. That can be equivalently expressed as follows:

$$V(S_j \geq S_i) = height(S_i \cap S_j) = u_{S_j}(d)$$

$$= \begin{cases} 1, & if \quad m_j \geq m_i \\ 0, & if \quad l_i \geq u_j \\ \dfrac{l_i - u_j}{(m_j - u_j) - (m_i - l_i)}, & \text{otherwise} \end{cases} \tag{8}$$

where *d* is the ordinate of the highest intersection point between $u_{Si}$ and $u_{Sj}$. We need to both the values of $V(S_j \geq S_i)$ and $V(S_i \geq S_j)$ to compare $S_i$ and $S_j$.

Step 4: We calculate the minimum degree possibility *d(i)* of $V(S_j \geq S_i)$ for *i,j=1,2,….,k* .

$$\begin{aligned} & V(S \geq S_1, S_2, S_3, \ldots\ldots, S_k), \quad for \quad i = 1,2,3, \ldots\ldots, k \\ & = V[(S \geq S_1) and (S \geq S_2) and \ \ldots\ldots (S \geq S_k)] \\ & = \min \ V(S \geq S_i) \quad for \quad i = 1,2,3, \ldots\ldots, k \end{aligned} \tag{9}$$

Assume that

$$d'(A_i) = \min \ V(S \geq S_i), \quad for \quad i = 1,2,3, \ldots\ldots, k \; .$$

Then the weight vector is defined as

$$W' = (d'(A_1), d'(A_2), \ldots\ldots\ldots, d'(A_n))^T \tag{10}$$

where $A_i$ *(i=1,2,…..,n)* are the *n* elements.

Step 5: We normalize the weight vectors. That is as follows.

$$W = (d(A_1), d(A_2), \ldots\ldots\ldots, d(A_n))^T \tag{11}$$

where *W* is a non-fuzzy number.

## 4 DEA

Data Envelopment Analysis is an evaluation tool used in conjunction with decision making units (DMUs) that effectively solves many decision making problems by simultaneously integrating multiple inputs and outputs. This mathematical method has enjoyed a wide range of applications since 1978. The DEA is generally applied not only to assess the service productivity of banks, insurance companies, hospitals, universities and restaurants, but also to evaluate the efficiency of R&D programs and to implement energy policy [6]. The hierarchy structure of the DEA process, which consists of a single input factor and multiple output factors. The input factor consists of the development cost associated with the development of hydrogen energy technologies. There are four output factors, namely economic impact, commercial potential, inner capacity, and technical spin-off. The relative weights calculated using the fuzzy AHP approach, are applied in conjunction with the output factors employed as part of the DEA approach. The DEA ration form, proposed by Charnes, Cooper and Rhodes, is designed to measure the relative efficiency or productivity of a specific $DMU_k$. The DEA formulation is given as follows. Suppose that there is a set of *n* DMUs to be analyzed, each of which uses *m* common inputs and *s* common outputs. Let *k* (*k*=1, 2, …, n) denote the DMU whose relative efficiency or productivity is to be maximized.

$$Max\ h_k = \frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \tag{12}$$

s.t

$$\frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \le 1,\ for\ \ \mathrm{j}=1,\ldots,\mathrm{n} \tag{13}$$

$$u_{rk} > 0,\ \text{for } r = 1,\ldots,s \tag{14}$$

$$v_{ik} > 0,\ \text{for } i = 1,\ldots,m \tag{15}$$

where $u_{rk}$ is the variable weight given to the $r^{th}$ output of the $k^{th}$ DMU, $v_{ik}$ is the variable weight given to the $i^{th}$ input of the $k^{th}$ DMU, $u_{rk}$ and $v_{ik}$ are decision variables determining the relative efficiency of $DMU_k$, $Y_{rj}$ is the $r^{th}$ output of the $j^{th}$ DMU, and $X_{ij}$ is the $i^{th}$ input of the $j^{th}$ DMU. This also assumes that all $Y_{rj}$ and $X_{ij}$ are positive. $h_k$ is the efficiency score, and is less than and equal to 1. When the efficiency score of $h_k$ is 1, $DMU_k$ is regarded as an efficient frontier. There are two types of CCR(Charne, Cooper, Rhodes) and BCC(Banker, Charnes, Cooper) models. One version is the input oriented model, in which inputs are maximized, and the other is the output oriented model in which the outputs are maximized. As the focus is on maximizing multiple outputs, this paper employs the output-oriented CCR and BCC model.

$$\min px_0 \tag{16}$$

$$\text{s.t}\quad qy_0 = 1 \tag{17}$$

$$-pX + qY \le 0 \tag{18}$$

$$p \ge 0,\ q \ge 0 \tag{19}$$

$x_o$ and $y_o$ are the input and output vector of $DMU_o$. In formular 18, X and Y variables mean that the matrix of inputs and outputs respectively. Let an optimal solution of $LP_o$ be (v*, u*), then an optimal solution of the output-oriented model is obtained from

$$p^* = \mathrm{v}^* / \theta^*,\ \mathrm{q}^* = \mathrm{u}^* / \theta^* \tag{20}$$

It is clear that (p*,q*) is feasible for $LP_o$. The optimal solution comes from the equation (21)

$$p^*x_0 = v^*x_0 / \theta^* = \eta^* \tag{21}$$

$$\hat{x}_0 = x_0 - t^{-*} \tag{22}$$

$$\hat{y}_0 = \eta^* y_0 + t^{+*} \tag{23}$$

t-* and t+* are the slack variables of input and outputs related to $DMU_0$.

There are various extension models of the CCR approach, among which the BCC model is representative. The BCC approach calculates the efficient frontier group spanned by the convex hull of the existing DMUs. In hence, the condition, which is eλ=1, is added in the CCR model considering the variable return to scale characterization, which accounts for increased return to scale(IRS), decreased return to scale(DRS), and constant return to scale(CRS).

The BCC output oriented model is expressed as from formular (24) to (27)

$$\min z = vx_0 \tag{24}$$

$$\text{s.t} \quad uy_0 = 1 \tag{25}$$

$$-uX - uY - v_0 e \geq 0 \tag{26}$$

$$v \geq 0,\ u \geq 0, v_0 \ \ \textit{free in sign} \tag{27}$$

In this research we applied the scale efficiency(SE) approach, which is based on the CCR and BCC scores, to measure the relative efficiency of 9 energy technologies in the sector of mid-term strategic energy technology development plan from a view point of the econometrics. Let the CCR and BCC scores of a DMU be $\theta^*_{CCR}$ and $\theta^*_{BCC}$ respectively. the SE is defined by the formular (28). SE is not greater than the maximum efficiency score one.

$$SE = \theta^*{}_{CCR} / \theta^*{}_{BCC} \tag{28}$$

For a BCC efficient DMU with CRS characteristics, its scale efficiency is one in the maximum scale size. The CCR efficiency score is called the global technical efficiency (TE), since it takes no account of scale effect as distinguished from pure technical efficiency(PTE). On the other hand, BCC expresses the local PTE under variable return to scale circumstances.

## 5 Numerical Example

We make pairwise comparisons of 4 criteria, which are economic impact, commercial potential, inner capacity, and technical spin-off, to evaluate hydrogen energy technologies in hydrogen ETRM. Table 1 shows the fuzzy evaluation matrix with response to the goal.

**Table 1: Fuzzy evaluation of the goal.**

| | EI | CP | IC | TS |
|---|---|---|---|---|
| EI | (1, 1, 1) | (1, 1, 1)<br>(2/3, 1, 3/2)<br>(1, 1, 1)<br>⋮ | (1, 1, 1)<br>(1, 1, 1)<br>(2/3, 1, 3/2)<br>⋮ | (2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>(3/2, 2, 5/2)<br>⋮ |
| CP | (1, 1, 1)<br>(2/3, 1, 3/2)<br>(1, 1, 1)<br>⋮ | (1, 1, 1) | (1, 1, 1)<br>(2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>⋮ | (2/3, 1, 3/2)<br>(1, 1, 1)<br>(3/2, 2, 5/2)<br>⋮ |
| IC | (1, 1, 1)<br>(1, 1, 1)<br>(2/3, 1, 3/2)<br>⋮ | (1, 1, 1)<br>(2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>⋮ | (1, 1, 1) | (2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>⋮ |
| TS | (2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>(2/5, 1/2, 2/3)<br>⋮ | (2/3, 1, 3/2)<br>(1, 1, 1)<br>(2/5, 1/2, 2/3)<br>⋮ | (2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>(2/3, 1, 3/2)<br>⋮ | (1, 1, 1) |

**Table 2: Fuzzy evaluation of criteria.**

| | EI | CP | IC | TS |
|---|---|---|---|---|
| EI | (1.00, 1.00, 1.00) | (0.93, 1.00, 1.10) | (1.03, 1.20, 1.40) | (1.00, 1.40, 1.90) |
| CP | (0.93, 1.00, 1.10) | (1.00, 1.00, 1.00) | (0.97, 1.20, 1.50) | (1.07, 1.40, 1.80) |
| IC | (0.81, 0.90, 1.03) | (0.75, 0.90, 1.13) | (1.00, 1.00, 1.00) | (0.67, 1.00, 1.50) |
| TS | (0.56, 0.80, 1.17) | (0.63, 0.80, 1.07) | (0.67, 1.00, 1.50) | (1.00, 1.00, 1.00) |

As a result of fuzzy evaluation of criteria, which is the mean value, is shown in Table 2. We calculate TFN values of 4 criteria by using the fuzzy evaluation values in Table 2. TFN values of criteria are as follow as an example:

$S_1$(Economic impact)=(3.97, 4.60, 5.40) $\otimes$ (1/20.20, 1/16.60, 1/14.01)=(0.20, 0.28, 0.39)

We compare the values of $S_i$ respectively and calculate the degree of possibility of $S_j$=( $l_j$, $m_j$, $u_j$) $\geq$ $S_i$=( $l_i$, $m_i$,$u_i$) by the formula (8). Table 3 shows the values of $V(S_j \geq S_i)$.

**Table 3: Values of ($S_j \geq S_i$).**

| $V(S_1>S_i)$ | value | $V(S_2>S_i)$ | value |
|---|---|---|---|
| $V(S_1 \geq S_2)$ | 1.00 | $V(S_2 \geq S_1)$ | 1.00 |
| $V(S_1 \geq S_3)$ | 1.00 | $V(S_2 \geq S_3)$ | 1.00 |
| $V(S_1 \geq S_4)$ | 1.00 | $V(S_2 \geq S_4)$ | 1.00 |
| $V(S_3>S_i)$ | value | $V(S_4>S_i)$ | value |
| $V(S_3 \geq S_1)$ | 0.72 | $V(S_4 \geq S_1)$ | 0.70 |
| $V(S_3 \geq S_2)$ | 0.74 | $V(S_4 \geq S_2)$ | 0.70 |
| $V(S_3 \geq S_4)$ | 1.00 | $V(S_4 \geq S_3)$ | 0.94 |

**Table 4: 10-point scale for IC and TS.**

| Scale | Definition |
|---|---|
| 2 | Inner capacity and technical spin-off are at an extremely low level |
| 4 | Inner capacity and technical spin-off are at a low level |
| 6 | Inner capacity and technical spin-off are at a medium level |
| 8 | Inner capacity and technical spin-off are at a high level |
| 10 | Inner capacity and technical spin-off are at an extremely high level |
| 1, 3, 5, 7, 9 | Intermediate values are used to compromise between two judgements |

We calculate the minimum degree possibility $d'(i)$ of $V(S_j \geq S_i)$ for $i,j=1,2,\ldots,k$ .

$D'(1)$=min $V(S_1 \geq S_2, S_3, S_4)$=min(1.00, 1.00, 1.00)=1.00, $D'(2)$= 1.00, $D'(3)$=0.72, $D'(4)$=0.70

Then the weight vector is like that:

$W' =(1.00, 1.00, 0.72, 0.70)^T$

We normalize the weight vectors. That is as follows:

$W =(0.29, 0.29, 0.21, 0.20)^T$

The final relative weights of 4 criteria, which are economic impact, commercial potential, inner capacity, and technical spin-off, are 0.29, 0.29, 0.21, and 0.20 respectively. In 4 criteria, economic impact and commercial potential are the most preferred criteria comparing with the other criteria through the result of Fuzzy AHP approach with making pairwise comparisons of 4 criteria.

**Table 5: 10-point scale for EI.**

| Scale | Definition |
|---|---|
| 2 | Potential energy saving is less than 10,000 TOE/year, $CO_2$ emission reduction is less than 10.000 $tCO_2$/year |
| 4 | Potential energy saving is between 10,000 and 500,000 TOE/year, $CO_2$ emission reduction is between 10.000 and 500.000 $tCO_2$/year |
| 6 | Potential energy saving is between 500,000 and 1,000,000 TOE/year, $CO_2$ emission reduction is between 500.000 and 1.000.000 $tCO_2$/year |
| 8 | Potential energy saving is between 1,000,000 and 2,000,000 TOE/year, $CO_2$ emission reduction is between 1.000.000 and 5.000.000 $tCO_2$/year |
| 10 | Potential energy savings is greater than 2,000,000 TOE/year, $CO_2$ emission reduction is greater than 5.000.000 $tCO_2$/year |
| 1, 3, 5, 7, 9 | Intermediate values are used to compromise between two judgements |

**Table 6: 10-point scale for CP.**

| Scale | Definition |
|---|---|
| 2 | Phase of quickening technology development, need arises to research new technological concepts |
| 4 | Phase of technology development, compent technologies need to be developed |
| 6 | Core patent acquirement phase |
| 8 | Commercialization phase, core patents can be obtained and technologies commercialized within 3 to 5 years |
| 10 | Technological dissemination phase, core patents can be acquired and technologies dissiminated within 3 years |
| 1, 3, 5, 7, 9 | Intermediate values are used to compromise between two judgements |

Shored listed hydrogen energy technologies are classified based on a 10-point scale. Table 4 shows the 10-point scale for inner capacity and technical spin-off. Table 5 and 6 display, respectively, the 10-point scale for economic impact and commercial potential. A single input and multiple outputs data, which is short listed hydrogen energy technologies, are described. The fuzzy AHP results multiples the 10 point scale and DEA approach is used to measure the relative efficiency of hydrogen energy technologies. We calculate the relative efficiency of hydrogen energy technologies by using the DEA approach in the second stage. Table 7 presents the relative efficiency scores and ranks of hydrogen energy technologies in the sector of hydrogen energy technology roadmap.

**Table 7: Relative efficiency of hydrogen energy technologies.**

| Low-level | Core technologie | CCR | BCC | SE | Rank |
|---|---|---|---|---|---|
| Hydrogen Production Tech | Hydrogen production tech from naturla gas | 1.000 | 1.000 | 1.000 | 1 |
| | Thermalchemical hydrogen production tech | 0.875 | 0.875 | 1.000 | 1 |
| | Water electrolysis hydrogen production tech | 0.840 | 0.875 | 0.960 | 10 |
| Hydrogen Separation & Storage Tech | Chemical storage tech of solid | 0.875 | 0.875 | 1.000 | 1 |
| | High purity hydrogen separation tech | 0.875 | 0.875 | 1.000 | 1 |
| PEMFC tech | Portable fuel cell tech | 0.926 | 1.000 | 0.926 | 13 |
| | Fuel cell vehicle tech | 1.000 | 1.000 | 1.000 | 1 |
| | Home/Industry system tech | 1.000 | 1.000 | 1.000 | 1 |
| DEFC tech | Micro fuel cell tech | 0.889 | 0.889 | 1.000 | 1 |
| | Laptop's fuel cell tech | 0.889 | 0.889 | 1.000 | 1 |
| | Portable power fuel cell tech | 0.889 | 0.889 | 1.000 | 1 |
| SOFC tech | Power generation fuel cell tech | 0.810 | 0.875 | 0.926 | 11 |
| | Home/APU fuel cell tech | 0.810 | 0.875 | 0.926 | 11 |

## 6 Conclusions

Hydrogen ETRM is a long-term strategic plan, which is established by KIER, coping with next 10 years from 2006 to 2015. We focus on the strategic development of hydrogen energy technologies as the only government sponsored research institute related to develop energy technologies in Korea. When governors or policy makers make an allocation of finite R&D budgets related to develop energy technologies strategically, it needs to allocate R&D budgets reasonably and scientifically. Through this extended research results, finite R&D budgets can be allocated with strategic approach for Korea's well focused R&D. In this research, we focus on the prioritization of hydrogen energy technologies and expound up how hydrogen energy technologies are measured the relative efficiency scores using 2-stage multi-criteria decision making approach, which accounts of fuzzy AHP and DEA approach with scale efficiency. For further study, we are planning to apply the fuzzy AHP and TOPSIS approach as an extended research.

**Acknowledgements**

This research is funded by the R&D funds of hydrogen energy R&D center, MEST, Republic of Korea.

**References**

[1] Lee SK, Mogi G, Lee SK, Kim JW. Prioritizing the weights of hydrogen energy technologies in the sector of the hydrogen economy by using a fuzzy AHP approach. IJHE 2010;doi:10.1016/j.ijhydene. 2010.01.035.

[2] Zadeh LA. Fuzzy sets. Information and Control 1965;8:338–53.

[3] Saaty TL. The Analytic Hierarchy Process. 1st ed. New York: McGraw-Hill; 1980.

[4] Lee SK, Mogi G. Kim JW. The competitiveness of Korea as a developer of hydrogen energy technology: The AHP approach, Energy Policy 2008;36(4):1284-1291.

[5] Lee SK, Mogi G, Kim JW. Decision support for prioritizing energy technologies against high oil prices: a fuzzy analytic hierarchy process approach. JLPPI 2009;22(6):915–20.

[6] Lee SK, Mogi G, Kim JW. Econometric analysis of the R&D performance in the national hydrogen energy technology development for measuring relative efficiency: The fuzzy AHP/DEA integrated model approach. IJHE 2010;35(6):2236-2246.

# Introducing Hydrogen as a Future Fuel: Strategies and Activities in Germany

**Oliver Ehret**, **Klaus Bonhoff**, National Organisation Hydrogen and Fuel Cell Technology, NOW GmbH, Fasanenstrasse 5, 10623 Berlin, Germany

## 1 Introduction

Hydrogen as a future fuel for road transport promises substantial cuts in greenhouse and other emissions, and reduced dependency from imports of mineral oil and other fossil fuels. Hydrogen can be produced from a multitude of energy sources, including wind and biomass, at competitive costs. Both fuel cell and hydrogen technologies imply attractive economic prospects. To support technological development and prepare for the market entry, the German Federal government set up the *National Innovation Programme Hydrogen and Fuel Cell Technology* (NIP). The *National Organization Hydrogen and Fuel Cell Technology* (NOW) assumes responsibility for programme management and assessment of funding applications. The study *GermanHy* answered the question how the future demand for low or no-carbon hydrogen for transport can be met at competitive costs. A strategy paper further discussed hydrogen supply paths and recommended future technology support activities. Studies and demonstration projects have started, regarding hydrogen produced from wind energy, hydrogen from biomass, and by-product hydrogen. The paper discusses the above issues, focusing on strategic developments and demonstration projects.

## 2 Innovation Programme and Programme Management

The NIP was set up by the German Federal Government in May 2006 [1]. The overall task of the programme is to support preparations for the market introduction of hydrogen and fuel cell technologies in the mobile and stationary sectors, as well as in special markets. The *Federal Ministry of Transport, Building and Urban Development* (BMVBS) contributes € 500 million for demonstration projects to the NIP. The *Federal Ministry of Economics and Technology* (BMWi) commits € 200 million for research and development (R&D) projects. The combined public funds worth € 700 million are to be matched by roughly the same amount contributed by the industry and other bodies running the projects. Thus, the NIP mobilizes a total of € 1.4 billion spread across the programme duration from 2007 to 2016. The *National Development Plan 2.1* (NEP) of April 2007 spells out the NIP and suggests a more precise agenda for technological development [5]. 54 percent of the NIP budget is allocated to mobile applications, including hydrogen production and infrastructure. The role of hydrogen is seen as a transport fuel and a storage medium for leveling out fluctuations in wind energy.

NOW was founded as the primary programme management organization in February 2008. Funding applications for demonstration projects are processed in close collaboration with the *Project Management Organization Jülich* (PTJ). NOW is in charge of the overall coordination of the NIP and the evaluation of project proposals in terms of content. PTJ is responsible for

R&D projects and formal aspects of demonstration projects. An important task of NOW is the development of strategies for technology development in collaboration with politics, science and industry [4]. Since March 2009, NOW also assumes responsibility for the *Model Regions Electric Mobility Programme* of the BMVBS (www.now-gmbh.de).

## 3 Hydrogen Production in the NEP

The *transport* chapter of the NEP recognizes the need to further develop the portfolio of hydrogen production technologies. Improvements in energy efficiency, cuts in carbon dioxide emissions, the diversification of the primary energies used for hydrogen production, and cost reductions are core programme goals. However, the NEP lacks detail where hydrogen production is concerned. Also, these issues are discussed as aspects of the wider transport chapter, rather than features in their own right.

Thus, it proved necessary to conduct a study investigating hydrogen production pathways, and to develop a strategy towards realizing the potentials once identified. In September 2009 the industry announced to introduce significant numbers of fuel cell vehicles (FCVs) in 2015 and to work towards building up large-scale infrastructure in initiatives such as *$H_2$ Mobility* (www.daimler.de). This calls for strengthening the profile of hydrogen production in the NEP.

## 4 The Study GermanHy

The study GermanHy answered the question ‘Where Will the Hydrogen in Germany Come from by 2050?’’ [2]. It established the volumes of hydrogen required to satisfy expected future transport fuel demands. GermanHy used different scenarios and calculated the share of the total production that individual pathways can account for between 2010 and 2050. The study considered established production technologies and such close to commercial availability only. A political imperative was that at least 50% of the total energy used had to be renewable.

The study showed that by 2050 up to 70% of all cars and light-duty vehicles in Germany could be equipped with fuel cells and that enough low or no-carbon hydrogen to fuel the vehicles could be made available. GermanHy also concluded that mobility based on fuel cells and hydrogen will be possible at today’s costs if the development targets for vehicles are met. The study estimates that hydrogen will cost between 4 and 5.5 €/kg in 2020, and between 3.5 and 4.5 €/kg in 2030. Carbon dioxide ($CO_2$) emissions of cars and light duty vehicles can be drastically reduced down to 40g $CO_2$/km (well to wheel) and 20g $CO_2$/km (tank to wheel) by 2050 (fleet average).

GermanHy showed how large volumes of hydrogen can be supplied as a transport fuel. However, it did not discuss in detail the technological, economic and environmental characteristics of the different supply paths. Moreover, the study did also not supply recommendations for action as to how to the potentials indentified could be realized. A Strategy Paper Hydrogen Production addressed these issues and is introduced below. The GermanHy findings with regard of the potential of individual production pathways - namely wind, coal, biomass, by-product and natural gas – are taken as a base.

## 5 Strategy Paper Hydrogen Production

The Strategy Paper Hydrogen Production was drafted by NOW and presented to the *Advisory Counci*l to NOW in September 2009. The Council is staffed by 18 representatives of politics, science and industry, and defines the agenda for technological development NOW has to pursue. A core task of the Council is to update the NEP. In December 2009 the Council decided to take the Strategy Paper as the base for revising the relevant parts of the NEP.

The Strategy Paper furnishes a detailed discussion of the GermanHy production pathways. Core items are the potential contribution individual paths can make, the state of the art of technologies, needs for further R&D and demonstration projects, and the activities of NOW. The paper aims at guiding activities ensuring that hydrogen production minimizes carbon emissions, relies on at least 50% renewable energy, increases energy efficiency, and achieves competitiveness of costs. Below the main pathways of the paper are discussed, taking account of recent comments of the Council.

According to all GermanHy scenarios electricity from off and on-shore wind power generators will play a central role in hydrogen production. Excess electricity that currently cannot be harvested due to insufficient capacities of the electricity grid can be used for electrolysis. The hydrogen produced can be used either as a vehicle fuel or be stored and reconverted into electricity at times of high demand. Wind hydrogen systems are especially important in light of plans to massively enhance wind power capacities in the future. Due to the high gravimetric storage capacity of hydrogen, large-scale underground storage of compressed hydrogen offers storage capacity for fluctuating energy unrivalled by other storage media. Several recent studies suggest that hydrogen is the only medium capable of storing the large volumes of fluctuating energy that will follow from increased wind power [6]. Electrolysers as the central components of wind hydrogen systems represent a key area for projects and studies supported by NOW. Large scale underground storage is another central issue for support in the future work of NOW.

GermanHy establishes that coal might evolve in an important source for hydrogen production as well; depending on the scenario either in conjunction with, or without, Carbon Capture and Storage (CCS). However, relevant technologies such as Integrated Gasification Combined Cycle power stations and CCS are not proven as yet. Both on the German and the European level clean coal technologies receive substantial governmental support. Given pronounced technological risks and existing support programmes, coal gasification is not regarded a priority theme for the NIP.

In all GermanHy scenarios biomass assumes relevance for hydrogen production, though its potential remains limited due to the relative scarcity of feedstock. Apart from generally low emissions, hydrogen production from biomass offers the advantage of the lowest costs of all pathways based on renewable energy. There is a multitude of different production processes with different characteristics, which complicates technology assessment. Gasification processes are generally regarded most promising, but also the reforming of substances such as biogas represents an interesting option [3]. A comparative evaluation of production processes is required. Today several small-scale R&D projects are running internationally, but just a few larger demonstration projects. There is a clear need for NOW to support relevant activities.

According to GermanHy, by-product hydrogen from the chemical industry can be readily made available at low costs. The volumes are small, but can be important in the early years of the market introduction of FCVs. A study suggests that there is enough hydrogen in the state of North Rhine Westphalia to fuel 6000 buses or 300.000 cars. Most technological components are state of the art and do not require major technological innovations. However, due to the importance by-product hydrogen can assume in facilitating the market entry of FCVs, NOW supports the production pathway.

In some GermanHy scenarios steam reforming of natural gas (SMR) makes a limited contribution to satisfy the hydrogen demand. In the light of expected rising gas prices and higher distribution costs associated with central SMR, GermanHy regards decentral SMR as the more viable option. However, there are pronounced technological and economic uncertainties. Therefore, SMR is not regarded a priority theme for the NIP.

## 6 Demonstration Projects and Studies on Hydrogen Production

In March 2010, 16 demonstration projects and studies regarding hydrogen production, worth € 68 million, are in discussion with NOW. 3 demonstration projects and 1 study with a combined budget of € 14 million received their final approval and have started.

The demonstration project *Renewable Hydrogen $RH_2$* shows the working of a wind hydrogen system set up and operated by the firm Wind-projekt and a subsidiary. Hydrogen is generated via electrolysis from wind energy, stored, and reconverted into electricity used to satisfy the power demand of wind generators during periods of calm (www.wind-projekt.de).

A study establishes the state of the art of water electrolysis, the central component of wind hydrogen systems. The main technologies AEL, PEMEL and HTEL are being evaluated in terms of performance, costs and requirements for technological improvements. Key players are being identified and recommendations for action are given.

A project on *Glycerin Reforming* by the gas company Linde uses glycerin produced as a by-product of bio-diesel production to generate hydrogen. Glycerin is purified, pyrolised and reformed in a pilot plant. The synthesis gas is then treated to hydrogen in existing industrial facilities for use in transport applications (www.linde.com).

The project *Chemergy* demonstrates how industrial by-product hydrogen can be made available for transport applications. The project run by the city of Hürth and partners treats by-product hydrogen from chlorine electrolysis to fuel cell standards, and dispenses the hydrogen in a filling station. The hydrogen is used in fuel cell buses operated in a complementary project funded by the state of North Rhine Palatine and the Netherlands (www.hycologne.de).

The demonstration projects and studies described above underline the priority NOW gives to hydrogen production from wind and biomass in strategy formulation and project activities. The activities target reduction of $CO_2$ emissions, reliance on renewable energy, high energy efficiency, and cost competitiveness.

**References**

[1] Bundesministerium für Verkehr, Bau und Stadtentwicklung [BMVBS], Bundesministerium für Bildung und Forschung, and Bundesministerium für Wirtschaft und Technologie (2006) Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie: 8 May (www.now-gmbh.de)

[2] Dena, FZK, ISI, LBST, Wuppertal Institut (2009) GermanHy: Studie zur Frage: ‚Woher kommt der Wasserstoff in Deutschland bis 2050?' im Auftrag von BMVBS und NOW GmbH: August (www.germanhy.de)

[3] Fachagentur für Nachwachsende Rohstoffe [FNR] (2007) Gülzower Fachgespräche: Band 25: Wasserstoff aus Biomasse (www.nachwachsenderohstoffe.de)

[4] Garche, J., Bonhoff, K., Ehret, O. and Tillmetz, W. (2009) 'The German National Innovation Programme Hydrogen and Fuel Cell Technology,' in Fuel Cells, No. 3, Special Issue, pp. 192-196

[5] Strategierat Wasserstoff und Brennstoffzellen [Strategierat] (2007) Nationaler Entwicklungsplan: Version 2.1 zum „Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie": 30 April (www.now-gmbh.de)

[6] Verband der Elektrotechnik Elektronik Informationstechnik [VDE] (2008) Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger: Bedeutung, Stand der Technik, Handlungsbedarf, December (www.vde.com)

# Development Status of Hydrogen and Fuel Cells - Europe

**Werner Tillmetz**, Zentrum für Sonnenenergie- und Wasserstoff- Forschung Baden-Württemberg (ZSW), Germany
**Ulrich Bünger**, Ludwig-Bölkow-Systemtechnik GmbH (LBST), Germany

In all world regions fuel cell vehicle commercialization has been announced to start after 2015 and to enter into mass production and full commercial markets after 2017. As much as fuel cell vehicles will enter the markets hydrogen must be provided by a supply infrastructure capable of providing customer satisfaction concerning access as well as acceptable prices as well as endorsement by the public sector with a view to safety and environmental performance.

Stationary fuel cell applications have already reached commercial status in some markets. Japan has e.g. started the commercial phase of combined heat and power (CHP) production based on residential fuel cells in 2009. About 10,000 residential fuel cells with a power level of 0.7 - 1 $kW_{el}$ provide Japanese homes with heat and electric power, thus saving more than 1 ton of $CO_2$ emissions per household and year.

This paper has the ambition to present some of the latest developments on those technologies of fuel cells and hydrogen of relevance mostly for Europe, both concerning the technology level reached as well as targets. In order to better understand the differences, these data are benchmarked against data and information published for other world regions where available to understand the regional differences.

Such a paper is prone to have deficits as the issue is highly dynamic and is coined by opinions of individual stakeholders. Instead of presenting a complete and 100% proven picture of the status quo we have the ambition to provide a screenshot Europe’s state-of-the-art in the international context by using some of the strategic work and interpreting some of the major discussions which have been carried out recently.

Even though detailed performance indicators for both vehicles and hydrogen infrastructure have been elaborated together with industry, e.g. by the European funded project HyLights, we will only address key performance indicators here.

## 1 Part I – Fuel Cells

Fuel cells will be used for transport and stationary applications as well as for special and diverse markets. Whereas, according to the results of a recent Japanese technology study on future fuel cell markets, early markets will be dominated by niche market products until 2018, residential fuel cell applications and transport applications will dominate by turnover with 90% by FY 2025. By then, the transport market for fuel cells will be double that for residential applications, totaling 13 billion € in Japan alone. Hence specific emphasis needs to be put on the transport market early in time.

## 1.1 Fuel cells for transport

The automotive industry today is the major driver of fuel cell development by spending billions of Euros in the advancement of the technology and preparing for series production. Almost all car companies worldwide and an increasing number of automotive suppliers are now involved in the development activities focusing on commercial sales from 2015 on. Since 2004 hundreds of fuel cell vehicles have been on the road under daily driving conditions and are being used by many different customers all around the world. Experience from millions of kilometers driven have been collected which create a solid base for the development of the next generation technologies. Meanwhile the second or even third generation of vehicles is on the road. These vehicles now meet nearly all automotive requirements like cold start capability from – 25°C, lifetime of more than 4,000 h, vehicle range per tank filling of more than 400 km and an excellent comfort of driving. Yet, two major hurdles have to be overcome in the near future: the set up of a hydrogen refueling infrastructure and the reduction of fuel cell system costs.

To address the first challenge a close collaboration between all stakeholders in industry and politics is needed. Therefore an important step was the signing of a Memorandum of Understanding, dubbed “H2-Mobility”, in September 2009 in Berlin involving relevant committed industry and the government. Also, projects such as the Clean Energy Partnership (CEP) under the umbrella of the German National Innovation Program on Hydrogen and Fuel Cells (NIP) form necessary platforms to support the transfer of today’s projects into broad commercial markets.

The cost reduction efforts are closely connected to the most relevant technical development goals, focusing on two major areas: The reduction of catalyst loading of the fuel cell while maintaining its durability and the simplification of the fuel cell system (balance of plant). Both developments will considerably benefit from the existence of a strong supply industry, which in the near future will also be a necessary prerequisite for an efficient series production of automotive fuel cell drive trains.

As the automotive industry is globally organized we expect no major strategic differences to occur between Europe, North-America and Asia. However governmental programs, existing in all major countries, will play an important role to bring all necessary stakeholders together and foster market entry.

## 1.2 Fuel cells for residential and industrial use

Fuel cells for residential power have experienced a major advancement in Japan, when entering the commercial phase in 2009. After a successful multi year field trial with about 3,000 units in operation, mostly Japanese industry with support from the Japanese government (NEDO) has decided to enter the commercial phase. Today only PEM fuel cells in combination with small integrated steam reformers for natural gas or LPG are being used. High temperature SOFC technology is somewhat lagging behind but is expected to pick up in the coming years. European activities are following with a delay of several years. The German CALLUX program is currently the singlemost strongest activity outside Japan. Within the first two years more than 50 units have been placed in the field – using PEM and SOFC technologies at equal numbers. The target is to have approximately 800 units in the field before starting the commercial phase by 2015.

Industrial CHP applications are dominated by the molten carbonate fuel cell (MCFC) technology having a major focus in the U.S. and Korea, where currently about 100 MW are under construction. They have reached the status of commercial sales, but are supported by governmental subsidies.

### 1.3 Fuel cells for special markets

While fuel cells have been demonstrated for almost all applications in special markets, only a few of them have by now also shown sufficient value proposition to become commercially successful.

In the area of emergency power supply or back up power, fuel cells in combination with hydrogen (stored as compressed gas in cylinders) offer an interesting additional benefit over today's lead acid batteries or Diesel generators. In terms of bridging time (time where power grid is off) and lowering maintenance costs hydrogen fuel cells have shown remarkable advantages. Telecommunication operators all around the world have started to implement fuel cells into their base stations. In Europe the most prominent activity relates to Denmark's TETRA-standard public safety communication network, where about 120 stations using a 1.7 kW PEM fuel cell system, have been taken into operation.

Material handling applications benefit from the fast "recharging" time of a fuel cell based drive system as compared to today's batteries. In the U.S., this has made some warehouse operators switch parts of their fork lift fleets to hydrogen operated fuel cells. Since the material handling industry is a low margin industry, such a change is only economically feasible with strong governmental subsidies. Europe, lacking such schemes for fuel cell applications until now has only demonstrated a few first prototypes, but is believed to also follow suit.

The commercially most successful fuel cell technology is the direct methanol fuel cell (DMFC) with dominant applications in the leisure market. The Munich based company SFC has so far sold 17,000 units fully commercially of their 50 - 100 $W_{el}$ fuel cell power pack system. Combined with a built-in lead acid battery of a motor home or a yacht can be supplied with sufficient electricity for daily use. Due to their high energy contents long operation periods without swapping methanol cartridges can be achieved. In addition, the logistics of methanol has been successfully implemented by SFC.

Further leisure markets, and specifically off grid power supply applications, are believed to become interesting future markets for the combination of a DMFC with a battery system. Due to their low power level in the application field, the specific investments for a fuel cell have a limited impact on the total application system costs. Several thousand hours lifetime have by now been achieved which is fully acceptable for most of the earmarked applications.

## 2 Part II – Hydrogen

This part focuses on the provision of hydrogen as a vehicle fuel as its availability at competitive costs is believed to be the most critical barrier to any one of the above cited fuel cell applications. Whereas energy performance (efficiency, $CO_2$-emissions) is believed to improve only gradually also in the long run specifically the costs of hydrogen delivery may vary widely depending on the pathway portfolio. Therefore, this part focuses mostly on the economic aspect of hydrogen delivery concluding with findings of a European–U.S. benchmark study.

To better understand the costs of hydrogen delivered as a vehicle fuel "to the pump" its major constituents need to be analyzed which are hydrogen production, hydrogen transport & distribution including processing and hydrogen refueling infrastructure.

### 2.1 Hydrogen production

Those hydrogen production processes which are relevant for short-term provision will be addressed here, being hydrogen as by-product from chemical production, hydrogen from steam methane reforming (central and onsite plants), hydrogen from alkaline water electrolysis (central and onsite plants), hydrogen from hard coal gasification with carbon capture and storage (CCS) and hydrogen from biomass gasification (decentral plants). Energy efficiency and plant capacity data for typical plants representing state-of-the-art in typical analysis work are presented in table 1.

**Table 1: Process efficiencies and plant capacities of representative hydrogen production plants.**

| | **Efficiency*** | **Capacity** |
|---|---|---|
| | [$kWh_{H2}/kWh_{in}$] | [$Nm^3/h$] |
| Hydrogen from steam methane reforming (central plant) | 0.71 | 100,000 |
| Hydrogen from steam methane reforming (onsite plant) | 0.69 | 222 |
| Hydrogen from alkaline water electrolysis (central plant, electricity from wind power) | 0.68 | 20,000 |
| Hydrogen from alkaline water electrolysis (onsite plant) | 0.625 | 60 |
| Hydrogen from biomass gasification (decentral and central plant) | 0.60 (central) 0.50 (decentral) | 85,000 (central) 1,330 (decentral) |

* Efficiency is calculated bearing the major energy input in mind, although other auxiliary forms of energy may also be used (e.g. natural gas in steam methane reformers)

Hydrogen production costs comprise capital and operating costs, the latter ones being dominated by the energy costs. To LBST's point of view all hydrogen cost data are to be interpreted with care as they heavily rely on primary energy price assumptions which are posed to vary greatly even in the short to medium term.

The following assumptions have been made in generating the charts below (hydrogen produced by gasification of hard coal, limited to CCS applications and therefore only relevant after 2020 at large scale, is not considered here):

- **Hydrogen from by-product:** Today, by-product hydrogen is used as a substitute for natural gas for electricity and heat production in industry. For by-product hydrogen to be used as transportation fuel it will be substituted by natural gas for electricity and heat generation and typically has to be purified and compressed before being used as FCEV fuel. Therefore, typically the costs of by-product hydrogen are identical to the price of natural gas plus the costs of hydrogen purification and compression if required. In 2009 the price for natural gas in the EU was about 2 to 5 €-cent/kWh.

- **Hydrogen from steam methane reforming (SMR):** SMR plant sizes can vary across broad production ranges. For illustration purposes a very large plant of 100,000 Nm³/hour and a small onsite plant at the fuelling station have been assumed. Natural gas is typically provided by the HP grid in large plants and the MP grid in small onsite plants. In some regions the SMR plant is an intrinsic part of the fuelling station, here it is listed separately.
- **Hydrogen from alkaline water electrolysis:** Both low and high pressure electrolysis are being used today, low pressure in large plants and low and high pressure in onsite plants. Plant sizes may vary flexibly, for illustration purposes both a large plant and an onsite plant are used here.
- **Hydrogen biomass gasification:** Even though large gasification plants have been analysed in the past, decentral plants in the order of 1,200 - 1,500 Nm³/hour are a realistic plant scale for European conditions.

For the most relevant hydrogen production processes from natural gas, electricity and biomass specific hydrogen cost data are presented in table 2. These figures are based on assumptions for the most recent WtW-studies by LBST [5], which all find their roots in the CONCAWE/EUCAR/JRC project database [1] but have been adapted to most recent cost assumptions.

**Table 2: Spec. plant investments and $H_2$ production costs for representative delivery pathways.**

| Path | Region | Spec. plant investment costs | Spec. $H_2$ costs*) | Target costs*) | |
|---|---|---|---|---|---|
| | | [€/$kW_{H2}$] | [€/$kWh_{H2}$] | [€/$kWh_{H2}$] | |
| Hydrogen from steam methane reforming (central plant) | Europe | 260 | 0.045 | | 1) |
| | U.S. | | | 0.042 - 0.064 | |
| Hydrogen from steam methane reforming (onsite plant) | Europe | 5,300 | 0.216 | | 2) |
| | U.S. | | 0.064 | 0.042 - 0.064 | |
| Hydrogen from alkaline water electrolysis (central plant, electricity from wind power) | Europe | 1,700 | 0.157 | | 3) |
| | U.S. | | 0.064 | 0.042 - 0.064 | From wind |
| Hydrogen from alkaline water electrolysis (onsite plant) | Europe | 2,000 | 0.197 | | 4) |
| | U.S. | | 0.112 | 0.042 - 0.064 | |
| Hydrogen from biomass gasification (decentral and central plant) | Europe | 600 (central) 2,900 (decentral) | 0.043-0.052 (central) 0.075-0.088 (decentral) | | 5) |
| | U.S. | | 0.042 | 0.042 - 0.064 | |

*) U.S. data and U.S. bandwidth for all production technologies taken from [2]

1) NG price 0.029 €/kWh (large industrial consumer), about 0.05 kWh of excess electricity are generated and fed into the electricity grid

2) NG price 0.04 €/kWh, electricity price 0.10 €/kWh, about 0.09 kWh of electricity are required per kWh of hydrogen

3) Electricity costs 0.065 €/kWh as typical for onshore wind power at locations with high wind speeds

4) Electricity costs 0.10 €/kWh

5) Biomass costs 60 - 80 € per ton of dry substance, decentral plant (10 $MW_{th}$ biomass input): besides hydrogen (4 MW) about 1 MW excess electricity and 1.6 MW of useable heat are generated, for the excess electricity credit of 0.09 € per kWh of electricity, for heat export 0.03 € per kWh of heat

It can be observed from comparing the European with the U.S. cost goals that typically the U.S. data is much lower. We interpret this to be the result of much lower energy price assumptions for the early commercialization phase.

## 2.2 Hydrogen transport and distribution

Currently three transport and distribution modes are being discussed, “trucking of compressed hydrogen (currently at 20 MPa)”, “trucking of liquefied hydrogen” and “distribution by pipeline”. Although in general transport contributes little to hydrogen costs at the pump, the necessary upfront investments are relevant as investments in infrastructure need to precede the arrival of fuel cell vehicle fleets. Whereas compressed and liquid hydrogen transport is believed to be the preferred short term option due to the lowest initial investments hydrogen pipeline transport is the cheapest transport option once a market has been established. Pipelines can either distribute hydrogen locally connecting individual fuelling stations with a regional hydrogen production site or transport hydrogen across longer distances. Hydrogen onsite generation builds on the transport of the primary energy to the fuelling station.

**Table 3: Specific hydrogen distribution costs.**

| | Liquid $H_2$ by trailer[1), 2)] | Compressed $H_2$ by trailer[2)] | $H_2$ by pipeline | Goal |
|---|---|---|---|---|
| | [€/$kWh_{H2}$] | [€/$kWh_{H2}$] | [€/$kWh_{H2}$] | [€/$kWh_{H2}$] |
| Europe | 0.029 | 0.032 | 0.02-0.03 | |
| U.S. | 0.059 | 0.064 | 0.048 | <0.021 |

1) Including $H_2$ liquefaction, electricity costs for $H_2$ liquefaction: 0.065 €/kWh, $LH_2$ trucking alone: 0.006 €/kWh (LHV).

2) Transport distance for $LH_2$ and $CGH_2$ truck: 150 km (one way in case of Europe)

## 2.3 Hydrogen refueling stations

Hydrogen refueling stations comprise a great variety of options by capacity and technology. Whereas in the early transition phase low capacity modular stations are needed they will grow in size with increasing vehicle density in highly populated areas. Fueling station utilization rates and economic learning by producing larger component and system numbers will be the most relevant factors determining the cost contribution to the hydrogen cost at the pump. Although investments are initially high they will be of little impact in a grown hydrogen fuel market.

**Table 4: Hydrogen refueling station investments and specific $H_2$ refueling costs.**

| | Small fuelling station* (100 kg/day) | | Medium size fuelling* station (300 kg/day) | | Large fuelling station* (1,000 kg/day) | |
|---|---|---|---|---|---|---|
| | Investment | Spec. $H_2$ cost | Investment | Spec. $H_2$ cost | Investment | Spec. $H_2$ cost |
| | [k€] | [€/$kWh_{H2}$] | [k€] | [€/$kWh_{H2}$] | [k€] | [€/$kWh_{H2}$] |
| Europe ($CGH_2$) | 570 | 0.035 | 670 | 0.035 | 1,930 | 0.035 |
| Europe ($LCGH_2$) | | | 670 | 0.029 | | |

* Without onsite hydrogen production (SAE J2601)

## 2.4 Hydrogen costs at pump

The cost of hydrogen at the pump is posed to decrease much as a consequence of better infrastructure utilization. The effect is twofold: On one hand technological learning by improving the process efficiency of mostly the production plants over time and economic learning by the sheer number of components or systems being deployed.

In order to accelerate the commercialization of fuel cell vehicles intelligent planning can support to bring down hydrogen costs at the pump rapidly. One way is to standardize components and systems, the other is to unify European or international regulations, codes &

standards both acting to accelerate economic learning, create competition among system suppliers as well as improve the safety in handling hydrogen in or close to the public.

When analyzing the cost contributions to the hydrogen cost at the pump it becomes obvious that they will be driven by production, distribution and retail contributions in the beginning, whereas in a later market phase will be mostly governed by hydrogen production.

In a benchmarking exercise in 2007 a full well-to-tank comparison of the most relevant hydrogen delivery chains has been analyzed in depth by a group of European and U.S. industry and research representatives under supervision of the U.S. DoE and the EC [4]. The results of this widely unrecognized study also represent a technological evolution over time as also deployment and cost curves have been taken into account. The results are presented in figure 1. Here the inner two columns for each pathway can be directly compared with each other as they have been normalized to similar assumptions. The major findings can summarized as follows:

- The similarity of figures shows high convergence of analysis results for these two important future markets for hydrogen and fuel cell vehicles,
- Except for the coal (with CCS) pathway hydrogen delivery costs for all other 8 pathways are very similar for the U.S. and Europe under harmonized financial calculation assumptions,
- Whereas maintenance and sometimes investment costs are typically higher in the U.S. assessment, energy costs are much more pronounced for the European study,
- An exception is onsite steam methane reforming for which it is believed in the U.S. that investments will be at low levels specifically in the early transition phase.

All hydrogen technologies have to be analyzed when applied to a specific context, i.e. hydrogen produced from electrolysis may become an important and even short-term option in countries or regions with ample and cheap (renewable) electricity whereas steam methane reforming of natural gas can be an economic short-term transition option or hydrogen from coal gasification including carbon capture and storage a long-term fossil option for countries with abundant coal resources. On the other hand and next to industry's preferences policymakers will consider sustainability (resource utilization, emissions) as criterion as e.g. in California where 33% of all hydrogen vehicle fuel must follow the renewable portfolio standard RPS imposed by California State Bill SB 1505 once surpassing a demand threshold.

Therefore hydrogen production will vary by source, delivery costs and $CO_2$-emission levels across regions. For the future control instruments will therefore need to be developed, creating the necessity to certify regional hydrogen fuel portfolios, preferencing the most economic and sustainable production pathways over time. To consider regional European diversity a representative supply portfolio in bandwidths for 10 member states had been developed by the European hydrogen roadmap project HyWays for a number of production pathways (figure 2) in 2030 indicating the potential options to reduce costs or GHG emissions.

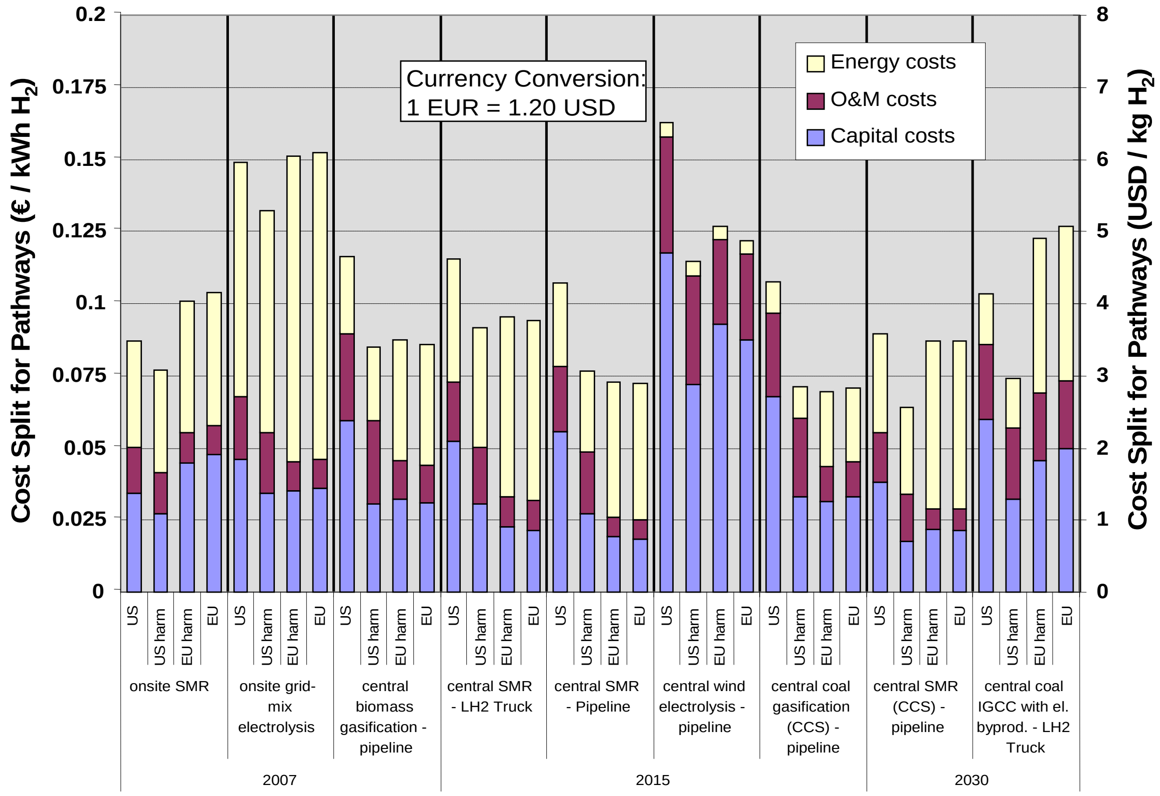



**Figure 1:** **Well-to-tank cost analysis of representative hydrogen delivery pathways – benchmarking of European and U.S. studies [4].**

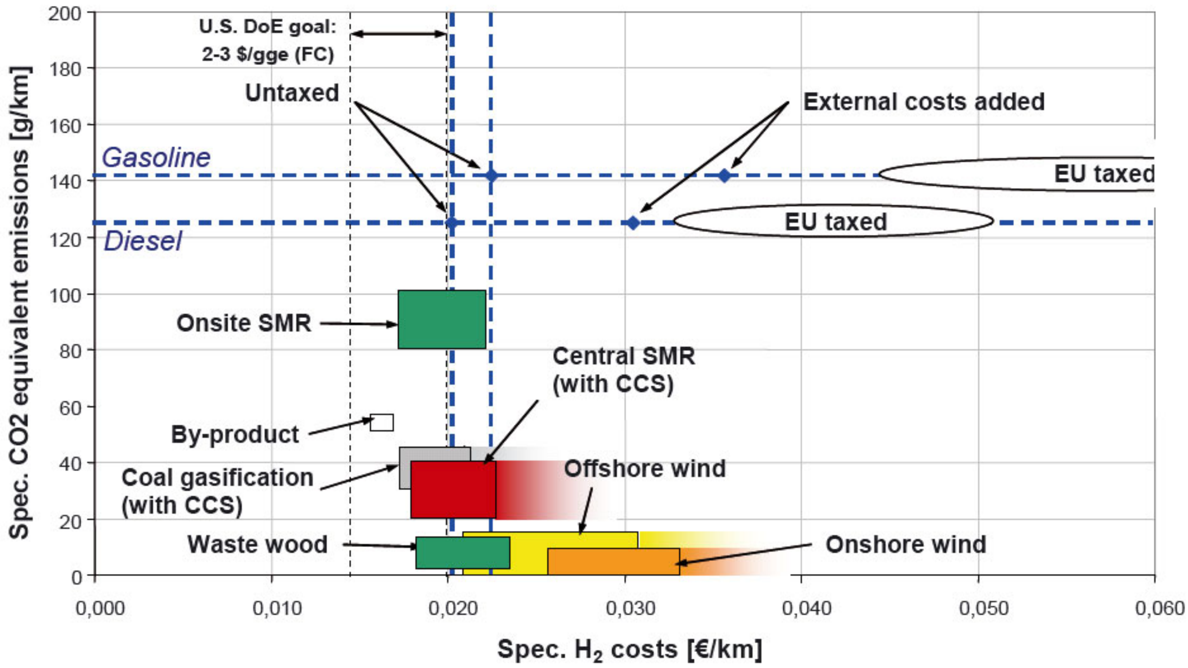



**Figure 2:** **Spec. GHG-emission/hydrogen cost portfolio for Europe in 2030 [3].**

**References**

[1] CONCAWE, European Council for Automotive R&D (EUCAR), European Commission Directorate General, Joint Research Center (JRC): Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context; Well-to-Wheels Report, March 2007; http://ies.jrc.ec.europa.eu/WTW.

[2] Garbak, U.S. DoE, IPHE Infrastructure Workshop, Sacramento, 25-26 Febr. 2010.

[3] European hydrogen roadmap study HyWays, 2008, http://www.hyways.de/.

[4] HyWays-IPHE: Comparing Hydrogen Analyses, EC Tech Review Days, Workshop Hydrogen Infrastructure Build Up, Brussels, 10 October 2007.

[5] Various hydrogen WtT and WtW analysis projects for industry based on [1]assumptions.

| | |
|---|---|
| SA | Strategic Analyses |
| SA.1 | Research & Development Targets and Priorities |
| SA.2 | Life-Cycle Assessment and Economic Impact |
| SA.3 | Socio-Economic Studies |
| SA.4 | Education and Public Awareness |
| SA.5 | Market Introduction |
| SA.7 | Regional Activities |
| SA.8 | The Zero Regio Project |

# Life Cycle Analysis and Economic Impact

Ulrich Wagner, Michael Beer, Jochen Habermann, and Philipp Pfeifroth

**Abstract**

This chapter presents a life cycle analysis of different potential fuels and power trains for passenger cars. The focus of the study is electric vehicles powered by batteries and fuel cells. First the cumulative energy demand (*CED*) is introduced as an instrument to compare the different technologies. Subsequently, several process chains for transportation are shown in a holistic approach. Finally, an economic and ecological comparison of the different drive technologies is used to work out the constraints and the necessary future development for hydrogen and electric power trains. The results are taken from several reports for the Bavarian Hydrogen Initiative (wiba), which is coordinated by the authors.

# Life Cycle Assessment of Hydrogen Production Processes: Steam Reforming of Natural Gas, Ethanol and Bioethanol

**Javier Dufour**, Department of Chemical and Energy Technology, Universidad Rey Juan Carlos, Spain
**David P. Serrano**, Department of Chemical and Energy Technology, Universidad Rey Juan Carlos and IMDEA Energía, Spain
**Jovita Moreno**, Department of Chemical and Environmental Technology, Universidad Rey Juan Carlos, Spain
**Jose Luis Gálvez**, National Institute of Aeroespace Technology (INTA), Renewable Energies Area, Spain

## 1 Introduction

Nowadays, natural gas is the main raw material for obtaining hydrogen through steam reforming. One of the most important environmental constraints of this process is related to its high greenhouse gases emissions. The global warming potential of this process can reach 13.7 kg $CO_2$ (equiv.) per kilogram of net hydrogen produced [1]. A part of these emissions is inherent to the process since $CO_2$ is a co-product in the main reactions involved: reforming reaction ($CH_4 + H_2O \leftrightarrows CO + 3H_2$) and water gas shift reaction ($CO + H_2O \leftrightarrows CO_2 + H_2$). The rest of the emitted $CO_2$ is related to natural gas extraction, processing of materials necessary for the plant, ancillary materials and energy consumption (heating, compression…) during the process.

In order to decrease these greenhouse gases (GHG) emissions some alternatives such as the implementation of $CO_2$ capture and storage (CCS) techniques and the use of others raw materials for the reforming reaction are being evaluated. For instance, steam reforming of ethanol is an attractive route because its high hydrogen content, easy-handling and low toxicity [2]. However, if the origin of ethanol is from fossil fuel, problems of $CO_2$ emissions remain being also necessary the use of CCS techniques. On the contrary, the use of bioethanol, easily produced via fermentation of biomass or agricultural waste products, is probably the most attractive alternative since $CO_2$ produced during its burning may be consumed during biomass growth [2].

When developing novel alternatives for hydrogen production, not only the reduction of $CO_2$ emissions and technical aspects must be taken into account, but the total environmental impact has to be also considered [3]. The main issue should be to establish which is the most environmentally-friendly process from a global point of view. In this sense, Life Cycle Assessment (LCA) is a powerful tool since it takes into account all the stages in the processes for hydrogen production, from the construction materials needed to erect the plants to the management of wastes generated during the operation.

In this work, hydrogen production through steam reforming of gas natural, ethanol and bioethanol including CCS techniques has been studied from a life-cycle point of view to determine which shows the best environmental performance from an overall point of view.

## 2 Systems Definitions and LCA Assumptions

The first system evaluated consists on the coupling of the methane steam reforming with $CO_2$ capture and storage (system called M-SR). An usual steam reformer is considered, operating at 1,100-1,200 K and 30 bar with a supported nickel catalyst, assuming that a 85 % conversion is obtained. The water gas shift reaction is carried out in two fixed beds working at high (773 K) and low temperature (573 K), respectively, with intermediate cooling [4]. Regarding to $CO_2$ capture and storage, it is assumed that $CO_2$ emissions from reforming are scrubbed with monoethanolamine, stripped, pressurized (130 bar) and injected in depleted oil and gas reservoirs [5].

Regarding to ethanol and bioethanol steam reforming (Et-SR and BIO-SR), the same process was considered for both cases by using a supported nickel catalyst at 773 K. Differences between both LCA studies are related to the ethanol origin: typical ethylene hydration and fermentation of sugar beets molasses, respectively. Processes associated with the land use (soil cultivation, sowing, fertilization, pest and pathogen control, etc.) as well as machine infrastructure necessary for sugar beets production were included in the inventory of bioethanol reforming. Likewise, processing of sugar beets to molasses at refinery including the treatment of effluents was also taken into account. Assumptions for $CO_2$ capture and storage after ethanol or bioethanol reforming were the same previously described for methane steam reforming.

For the three LCA studies, the selected functional unit is 1 $Nm^3$ of hydrogen (99.99% purity). The life cycle assessment is focused on the raw material, energy acquisition and manufacturing stages, as distribution, use and end-of-life stages are supposed to be the same for the three processes. The construction materials needed to erect the production plants are also considered. In order to perform a correct inventory for the LCA, systems under study were simulated determining the inputs (raw materials and energy) and outputs (materials, wastes and emissions) for each plant. The assessment was carried out with SimaPro 7.1 software by using the eco-invent 2.0 database. The Eco-indicator 99 method was used for impacts classification and characterization. This method takes into account the environmental effects that damage the human health, ecosystems quality and natural resources such as greenhouse effect, ozone layer depletion, carcinogens and respiratory effects, radiation, eco-toxicity, acidification, eutrophication, land use and consumption of minerals and fossil resources.

## 3 Results and Discussion

Table 1 shows the results of LCA´s for the three systems by using the above mentioned Eco-indicator 99 method. According to this methodology, the greenhouse effect, ozone layer depletion, respiratory effects and radiation are expressed as DALY (Disability Life Years, effects on human health); the eco-toxicity as PAF (Potentially Affected Fraction, effect on ecosystem quality); the acidification, eutrophication and land use as PDF (Potentially Disappeared Fraction, effects on ecosystem quality) and the consumption of minerals and fossil resources as surplus energy necessary for future extractions of low quality minerals and fossil resources (MJ surplus, effects on available resources).

Regarding to the effects on human health of the three processes, it is very remarkable the reduction of climate change achieved by bioethanol reforming. This result indicates that biomass growth allows fixing more $CO_2$ than the produced in the subsequent processes. However, as can be seen in the Figure 1, others impacts that damage the human health such as respiratory effects and radiation are higher for steam reforming of bioethanol than for M-SR and Et-SR processes. The production and use of fertilizers and pesticides necessary for the cultivation step are probably responsible of these higher DALY values.

**Table 1: LCA results by using Eco-indicator 99.**

| Impact category | Unit | M-SR | Et-SR | BIO-SR |
|---|---|---|---|---|
| Respiratory effects | DALY | 2.637E-07 | 3.378E-07 | 4.140E-07 |
| Climate change | DALY | 1.023E-07 | 1.346E-07 | -1.162E-07 |
| Radiation | DALY | 2.623E-09 | 2.890E-09 | 6.602E-09 |
| Ozone layer | DALY | 2.357E-10 | 1.555E-11 | 5.739E-11 |
| Eco-toxicity | PAF*m$^2$yr | 3.559E-02 | 1.169E-02 | 5.048E-02 |
| Acidification/ Eutrophication | PDF*m$^2$yr | 7.991E-03 | 9.708E-03 | 2.090E-02 |
| Land use | PDF*m$^2$yr | 6.762E-03 | 1.788E-03 | 5.327E-01 |
| Minerals | MJ surplus | 5.535E-03 | 4.075E-03 | 1.542E-02 |
| Fossil fuels | MJ surplus | 4.243 | 3.749 | 0.896 |

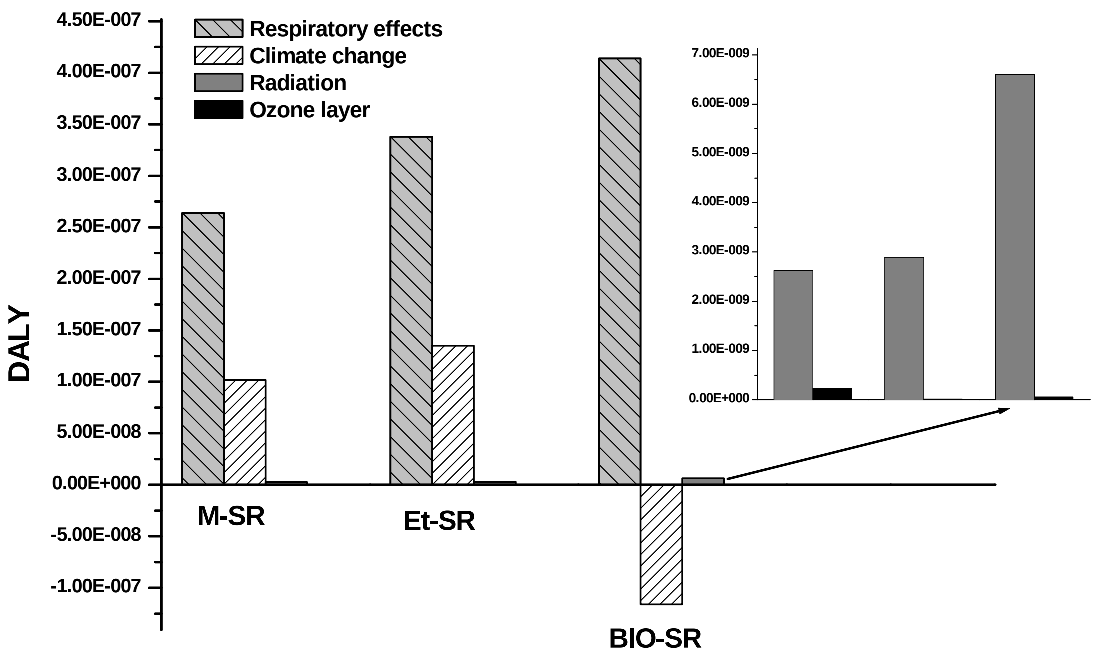



**Figure 1: Effects on human health of M-SR, Et-SR and BIO-SR processes (Eco-Indicator 99).**

Figure 2 shows the impacts on the ecosystem quality of the three processes indicating that bioethanol steam reforming leads to more acidification, eutrophication and eco-toxicity than M-SR and Et-SR. As known, the application of fertilizers and pesticides on the land for improving its cultivation capacity and controlling pathogen populations favours the acidification and eutrophication and increases the environment toxicity for a lot of species. Some authors propose that acidification is mainly caused by atmospheric $NH_3$ emissions coming from nitrogen of fertilizers [6] whereas others investigations suggest that emissions from diesel of agricultural machinery have also an important contribution to this effect [7]. Regarding to the eco-toxicity, results previously reported also indicate that it is widely increased by agricultural activities due to production of fertilizes and emissions of pesticides [7, 8].

Eco-indicator 99 methodology is recommended for the evaluation of processes which include cultivation stages since it takes into account an important penalty for the land use. In this case, it is obvious that environmental impact associated with the land use must be much higher for bioethanol reforming than for M-SR and Et-SR processes due to the biomass cultivation step.

The results obtained for the use of mineral and fossil resources are especially remarkable (see Table 1). Despite reforming of bioethanol consumes more minerals than the other two processes due to the utilization of fertilizers, it presents much lower fossil fuel consumption. These results are related to the raw materials used for each system: biomass for BIO-SR and methane and ethylene coming for the oil for M-SR and Et-SR, respectively, and the reuse of biomass wastes to produce energy.

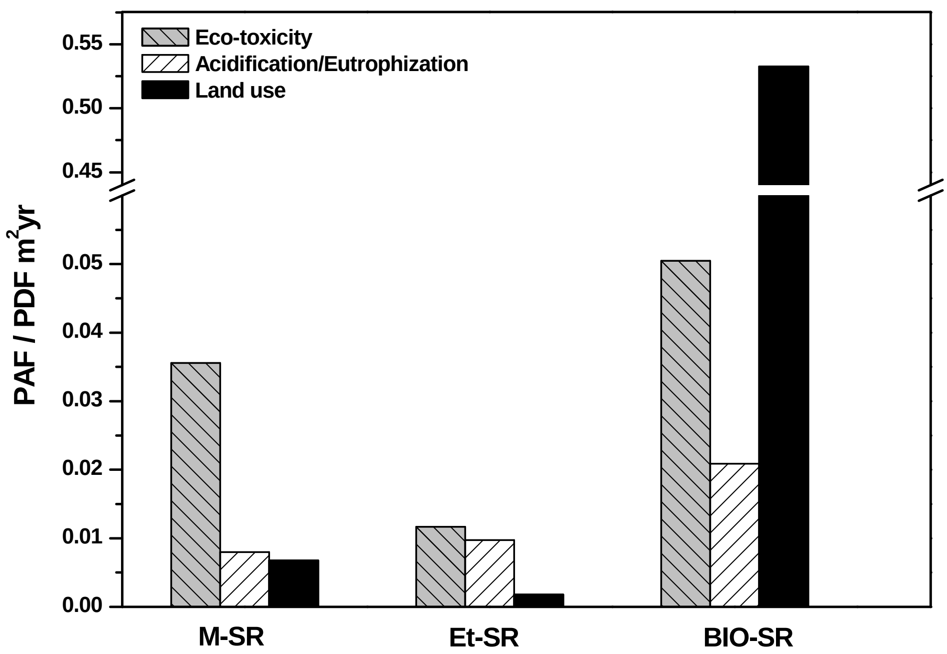



**Figure 2: Effects on ecosystems quality of M-SR, Et-SR and BIO-SR processes (Eco-Indicator 99).**

Finally, Figure 3 shows the single score for the three processes calculated according to Eco-indicator 99 methodology, after normalization (factors 65,4 for human health categories, $1.95 \cdot 10^{-4}$ for ecosystems quality categories and $1.19 \cdot 10^{-4}$ for resources ones) and weighting (400, 400 and 200, respectively). It can be observed that the most environmental-friendly process is the reforming of bioethanol. That means the high environmental impacts associated with the production and utilization of fertilizers and pesticides and land use are clearly compensated by the low consumption of fossil fuels and the capture of $CO_2$ during biomass growth.

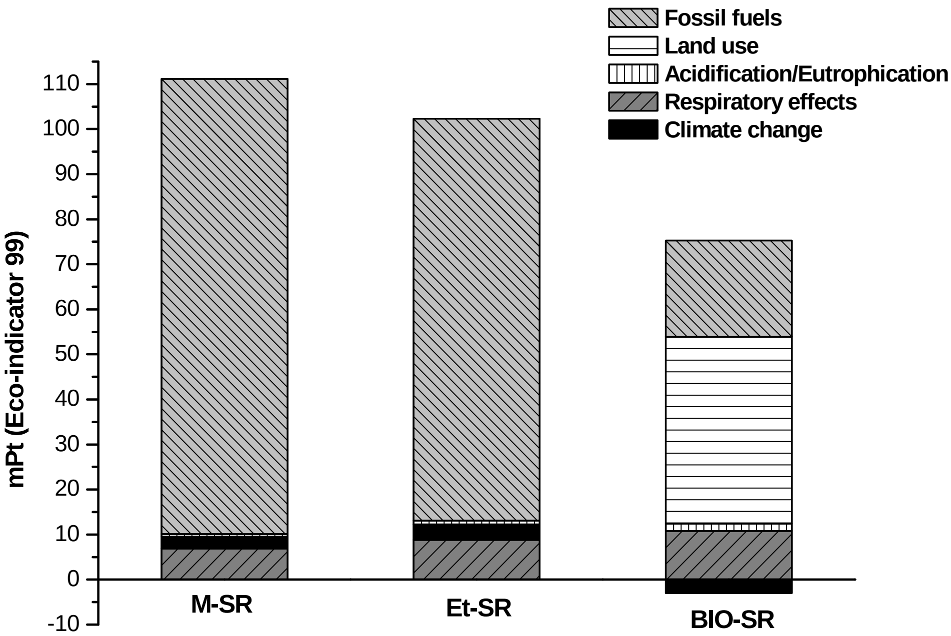



**Figure 3: Single score of M-SR, Et-SR and BIO-SR processes (Eco-Indicator 99).**

The conclusion that bioethanol steam reforming is the most environmental-friendly process from a global point of view is important since not always processes which lead to less greenhouse gases emissions also present the lowest single score. For instance, previous works have showed that the incorporation of $CO_2$ capture and storage techniques to the conventional methane steam reforming allows a great decrease of $CO_2$ emissions but leads to a slight increase of the process total single score (principally due to higher NOx emissions associated with the high electricity consumption) [3]. But in this case, even by using a methodology as Eco-indicator 99 which penalties the land use (and, therefore, the cultivation stages), the reforming of bioethanol seems to be the most environmental-friendly option for hydrogen production.

## References


[1] N.Z. Muradov and T.N. Veziroglu. Int. J. Hydrogen Energy 30 (2005) 225-237.

[2] J. Comas, F. Mariño, M. Laborde and N. Amadeo. Chem. Eng. J. 98 (2004) 61–68.

[3] J. Dufour, D.P. Serrano, J.L. Gálvez, J. Moreno and C. García. Int. J. Hydrogen Energy 34 (2009) 1370-1376.

[4] P.M. Spath and M.K. Mann. National Renewable Energy Laboratory. Report NREL/TP-570-27637, 2001.

[5] N. A. Odeh and T.T. Cockerill. Energy Policy 36 (2008) 367-380

[6] F. Cherubini and G. Jungmeier. Int. J. Life Cycle Assess 15 (2010) 53-66

[7] S. González-García, C.M. Gasol, X. Gabarrell, J. Rieradevall, M.T. Moreira and G. Feijoo. Renew. Energy 35 (2010) 1014-1023.

[8] I. Muñoz, M.M. Gómez and A.R. Fernández-Alba. Agric. Syst. 103 (2010) 1-9.

# Societal Cost-Benefit Analysis of Transportation Options in a Carbon-Constrained World

**C.E. (Sandy) Thomas**, H2Gen Innovations, Inc., USA

Many alternative vehicle and fuel options are under consideration to alleviate the triple threats of climate change, urban air pollution and petroleum dependence caused by operating motor vehicles. We report the results of a dynamic computer simulation model comparing the societal costs and benefits of biofuels, hybrid electric vehicles, plug-in hybrids, fuel cell electric vehicles and battery electric vehicles over the 21$^{st}$ century. We conclude that all-electric vehicles will be required to reduce greenhouse gas emissions by 80% below 1990 levels as shown in Figure 1, to eliminate most oil consumption from motor vehicles, and to eliminate most controllable urban air pollution. Partial electrification via hybrids and plug-in hybrids help, but we must eventually discard the venerable internal combustion engine to meet our societal goals. There are two primary choices for all-electric vehicles: batteries or fuel cells. We show that for reasonable travel range, hydrogen-powered fuel cell electric vehicles are superior to battery electric vehicles and provide greater societal benefits at lower cost. For example, Hydrogen-powered FCEVs would reduce total US societal costs by total US annual societal costs due to pollution and dependence on imported oil could be reduced by over $319 billion by the end of the century with hydrogen-powered FCEVs compared to a base case using only hybrid electric vehicles (HEVs) as shown in Figure 2, while gasoline-powered plug-in hybrid electric vehicles (PHEVs) would at best cut societal costs by $134 billion per year by 2100 as shown in Figure 2. BEVs, if they could power all US vehicles (including light-duty trucks and SUVs) would cut societal costs by $300 billion, still less than the FCEV societal cost reduction of $319 billion per year by the end of the century.

In addition to FCEVs reducing societal costs more than BEVs, GHGs and oil imports, FCEVs would cost less (according to Kromer and Heywood of MIT in their 2007 report, FCEVs would cost $6,600 less than BEVs in mass production) and the US Government infrastructure incentives needed for a distributed hydrogen fueling infrastructure would be less (US$831 million) than the government incentives required to install public charging stations for BEVs (US$1.12 billion).

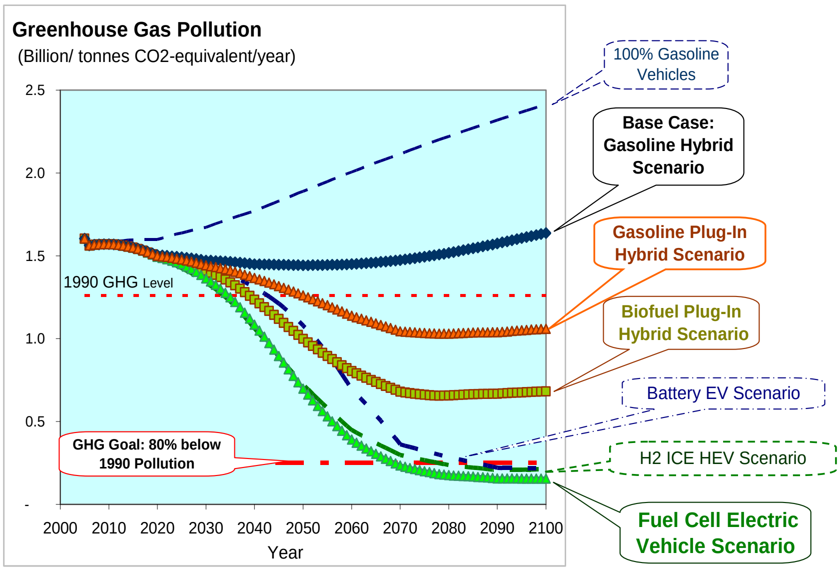



**Figure 1:** **Greenhouse gas pollution from light duty vehicles in the US over the 21st century with different alternative vehicle options; adding only hybrid electric vehicles (HEVs) to the fleet increasess GHGs to 30% above 1990 levels by the end of the century. Adding plug-in hybrid electric vehicles (PHEVs) to the mix would cut GHGs to 175% below 1990 levels, and fueling PHEVs with biofuels would reduced GHGs to 46% below 1990 levels levels. Hydrogen-powered ICE HEVs would cut GHGs to 75% below 1990 levels, and battery electric vehicles (BEVs) would reduce GHGs to 83% below 1990 levels, assuming that BEVs could be used in all US vehicles including light duty trucks, sports utility vans (SUVs). Adding Hydrogen-powered fuel cell electric vehicles (FCEVs) would cut GHGs to 87% below 1990 levels by the end of the century.**

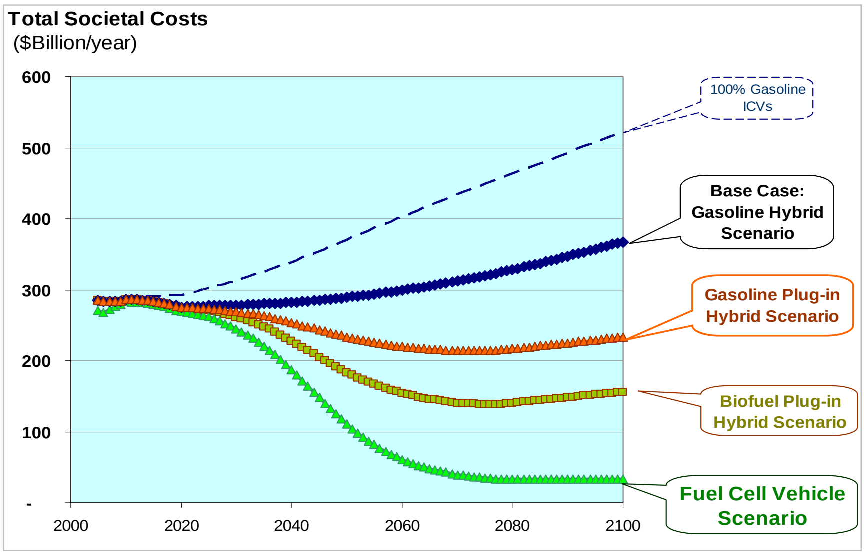



**Figure 2:** **Estimated total societal costs in the US due to local air pollution, greenhouse gas emissions and the economic and military costs of protecting access to imported oil**

# Analysis of Energy Consumption and $CO_2$ Emissions of the Life Cycle of Bio-hydrogen Applied to the Portuguese Road Transportation Sector

**Ana Filipa Ferreira**, **Patrícia Baptista**, **Carla Silva**, IDMEC, Dept. Mechanical Engineering, Instituto Superior Técnico, Portugal

In this work the main objective is to analyze energy consumption and $CO_2$ emissions of bio-hydrogen for use in the transportation sector in Portugal. A life cycle assessment will be performed in order to evaluate bio-hydrogen pathways, having biodiesel and conventional fossil diesel as reference. The pathways were production of feedstock, pre-treatment, treatment, compression, distribution and applications. For the well-to-tank analysis the SimaPro 7.1 software and excel tools are used. This study includes not only a well-to-tank analysis but also a tank-to-wheel analysis (using ADVISOR software) estimating hydrogen consumption and electricity consumption of a fuel cell hybrid and a plug-in hybrid. Several bio-hydrogen feedstocks to produce hydrogen through fermentation processes will be considered: potato peels.

To estimate the environmental impacts of hydrogen vehicles we consider all emissions associated with the system. The following environmental effects are considered: greenhouse gas emissions and energy consumption. Life Cycle assessment is an analytic tool for quantifying the environmental impacts of all processes used in converting raw materials into a final product [7, 8]. The LCA of the considered fuels was divided in two stages: well-to-tank (WTT) and tank-to-wheel (TTW). WTT considers the fuel from resources recovery to delivery to the vehicle tank. The methodology for the WTT for bio-hydrogen includes the following 5 processes: production of feedstock, fuel production (pre-treatment and treatment), compression and distribution. The pre-treatment and treatment correspond to hydrolysis and fermentation processes respectively. The feedstock to produce hydrogen through fermentation process is potato steam peels as carbon sources. The process for the production of biohydrogen differs primarily concerning the involved microorganisms, the substrate and the light dependence. In this case study the technology considered is bioreactors. The potato steam peels are introduced in the bioreactor where they are hydrolyzed to glucose. This is introducing into the thermoreactor containing thermophilic bacteria. The residual solids of the thermoreactor are introduced in photoreactor containing photoheterotrophic bacteria that convert all organic acids to $H_2$ and $CO_2$ [9].

The hydrogen gas has to be compressed to the required pressure. If no heat exchange with the environment is assumed, the compression is adiabatic [10]. Then for estimate energy emission of compression (isentropic compression) used the Equation 1.

$$(W)_{isen} = \frac{nRT_1}{k-1}\left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right)$$

Equation 1: Compression equation

Where the k is adiabatic exponent, n is amount of moles, R is real gas constant, $T_1$ is the temperature in the suction, $P_1$ is a suction pressure and $P_2$ is final (delivery) pressure. In the study case was considering that compression efficiency is about 68%. Hydrogen is compressed at 45 MPa [10].

The pathway considers potatoes produced in Portugal, that average productivity (from 1986 to 2008) is 13 790 kg $ha^{-1}$ [11]. We considered that potato peels are 35% of potato production [12]. Hydrogen pathway is resumed in Figure 1.

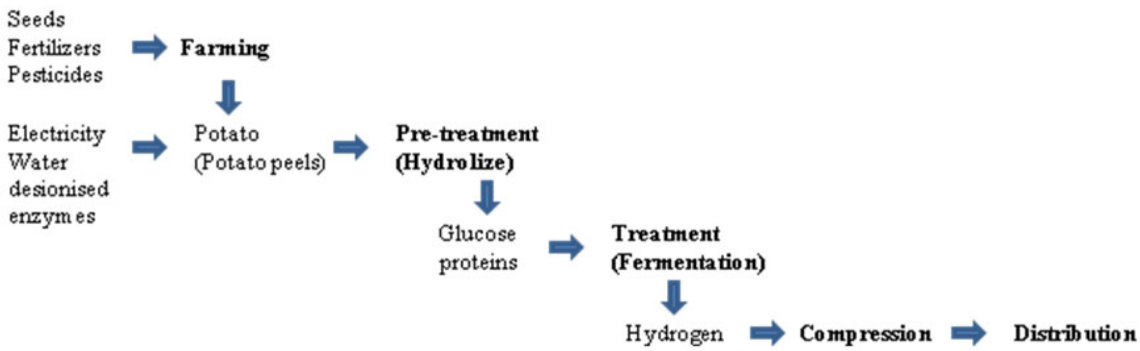



**Figure 1: Bio-hydrogen fuel pathway.**

This case study considers emissions from the electricity used in hydrogen pathways steps. Electricity consumed in all processes is assumed to come from power mix for Portugal.

The energy consumption and $CO_2$ emissions for all processes are calculated based on SimaPro software data. The energy spent (MJ/MJfuel) in each of the processes calculated in the present study excludes the energy transferred to final fuel. $CO_2$ emissions (g/MJfuel) of the processes do not include the $CO_2$ capture during the crops "agricultural" or algae production stage. A life cycle assessment will be performed having biodiesel and conventional fossil diesel as reference. The three biodiesel studied were [13]:

- Sunflower – the only Portuguese native crop considered for massive biodiesel production. However, considering the maximum land occupancy (from 1980 to 2007), only 6% of the consumed diesel would be replaced.
- Blended rapeseed and soybean biodiesel – Portugal inevitable has to import oil seed crops for biodiesel production, which contradicts many of the sustainability issues in by lorry to Portugal and American soybean shipped to Portugal. A typical oil blend of rapeseed (60%) and soybean (40%) was considered for biodiesel production.
- Microalgae biodiesel – microalgae could become a suitable alternative due to its high biomass production and $CO_2$ fixation. Nonetheless, it is not a mature technology so

few accurate data is available. The technology considered were photobioreactors and average yields for algae productivities and oil content were considered.

This study will include not only a well-to-tank analysis but also tank-to-wheels, since the vehicle usage simulation will also be performed. TTW is assessing vehicle architecture, power train and fuels effects. The program ADVISOR was used to simulate the energy consumption and emissions of each vehicle in the specified driving cycle.

The vehicle specifications are [14]:

- Hybrid (FC-HEV): fuel cell vehicle with a 75 kW electric motor, Li-ion 6 Ah 267 V battery, 50 kW fuel cell and a total weight of 1388 kg;
- Plug-in hybrid (FC-PHEV): lightweight materials, plug-in series hybrid with fuel cell. Fuel cell stack 50 kW, electric motor 75 kW, battery Ni-MH 45 Ah 335 V and a total weight of 1315 kg.
- Internal Combustion Engine Vehicle (ICEV): internal combustion engine vehicle that can run with diesel and blends of diesel and biodiesel B10 with a four cylinder Diesel engine with 67 kW of power and total weight of 1210 kg.

These vehicles have a total power-to-weight ratio of 55 W/kg since this is representative of the top sales of new vehicles sold in Portugal, with whom these new technologies will compete when they start entering the market. Additionally, it guarantees that similar vehicle performances are being compared.

The used driving cycle is a real measured driving cycle, representing a mix of urban (24% of km, speed below 50 km/h), rural (57% of km, speed between 50 and 90 km/h), and highway (19% of km, speed higher than 90 km/h) driving. Figure 2 shows the journey driving cycle.

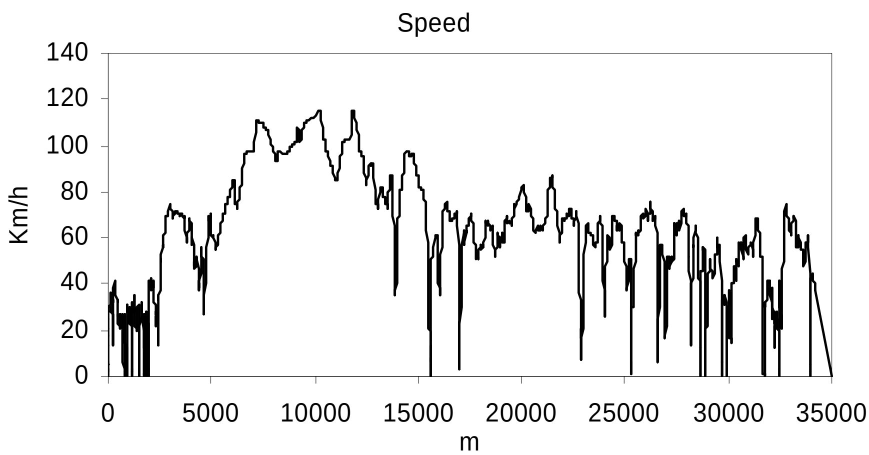



**Figure 2: Drive cycle.**

The WTT results for energy and global warming gases for life cycle stages farming, “pre-treatment”, “treatment”, compression and distribution of hydrogen production from potato steam peels are present in Figure 3.

In figure 3, results show that Treatment (fermentation) and Pre-Treatment (hydrolysis) are the most energy consuming processes and with higher $CO_2$ emissions. In these two stages of the production of hydrogen were spent 8.05 g $CO_2$/ $MJ_{fuel}$ and 0.33 MJ/ $MJ_{fuel}$, respectively.

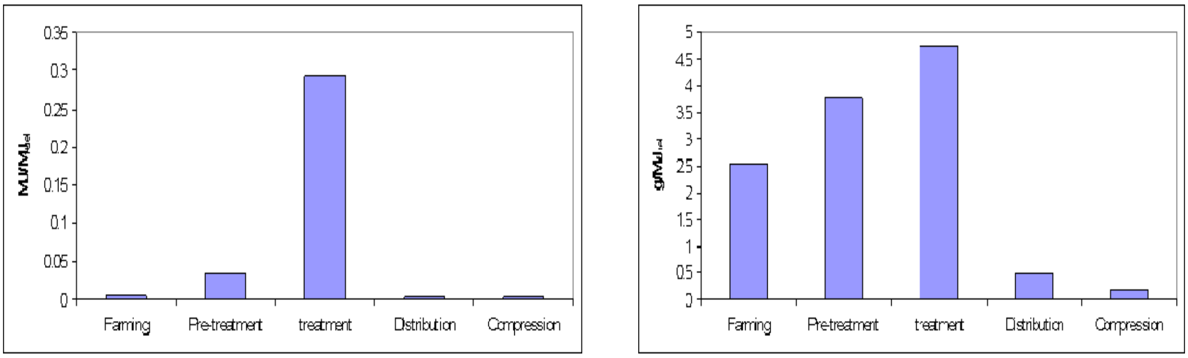



**Figure 3: Energy and global warming gases for life cycle stages farming, "pre-treatment", "treatment", distribution and compression of hydrogen production from potato peels.**

The total energy consumption of the WTT pathways doesn't include the energy content of the produced fuel. When comparing the different pathways of production of biologic hydrogen, biodiesel and diesel, different value for energy and $CO_2$ emissions are achieved. As it can be seen in figure 4, the diesel production pathway has the lowest values of energy consumption, and has balanced $CO_2$ emissions with the hydrogen pathway when produced from potato peels, but both with the lowest values.

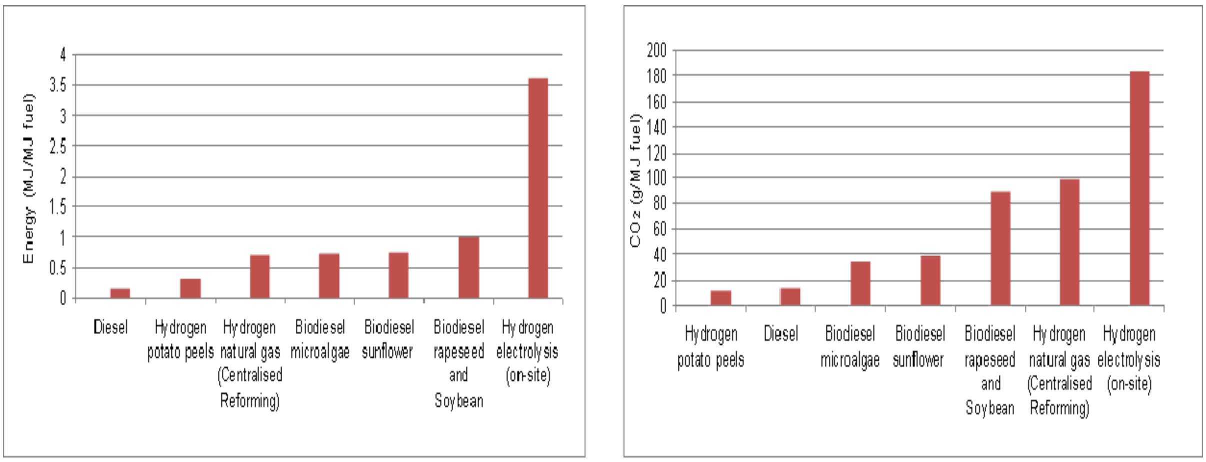



**Figure 4: WTT energy consumption and $CO_2$ emissions of hydrogen, diesel and biodiesel fuels.**

The TTW values are taken from the other study (14) as seen in table 1.

**Table 1: Fuel life cycle energy and $CO_2$ WTT, TTW and WTW results for fuel cell hybrid and hybrid plug-in and hybrids plug-in diesel.**

| Technology-Fuel | WTT (MJ/MJfuel) | WTT ($gCO_2$/MJfuel) | TTW (MJ/km) | TTW ($gCO_2$/km) | WTW (MJ/km) | WTW ($gCO_2$/km) |
|---|---|---|---|---|---|---|
| ICEV- Diesel | 0.16 | 14.00 | 1.67 | 124.40 | 0.27 | 147.78 |
| ICEV-B10-Sunflower | 0.22 | 16.50 | 1.63 | 110.70 | 0.36 | 137.60 |
| ICEV-B10-microalgae | 0.22 | 16.10 | 1.63 | 110.70 | 0.36 | 136.94 |
| ICEV-B10-Rapeseed and Soybean | 0.24 | 21.60 | 1.63 | 110.70 | 0.40 | 145.91 |
| FC-HEV-hydrogen Centralized Reforming | 0.72 | 99.10 | 1.08 | 0.00 | 0.78 | 107.03 |
| FC-HEV-hydrogen Electrolysis (on-site) | 3.62 | 184.21 | 1.08 | 0.00 | 3.91 | 198.95 |
| FC-HEV-hydrogen Potato Peels | 0.34 | 11.72 | 1.08 | 0.00 | 0.36 | 12.66 |
| FC-PHEV- hydrogen Centralized Reforming | 0.72 | 99.10 | 0.34 | 0.00 | 0.24 | 33.69 |
| FC-PHEV-hydrogen Electrolysis (on-site) | 3.62 | 184.00 | 0.34 | 0.00 | 1.23 | 62.56 |
| FC-PHEV-hydrogen Potato Peels | 0.34 | 11.72 | 0.34 | 0.00 | 0.11 | 3.99 |
| FC-PHEV- electricity | 1.47 | 101.78 | 0.21 | 0.00 | 0.31 | 21.37 |
| FC-PHEV- hydrogen Centralized Reforming+electricity | 1.00 | 100.12 | 0.55 | 0.00 | 0.55 | 55.07 |
| FC-PHEV-hydrogen Electrolysis (on-site) + electricity | 2.80 | 152.76 | 0.55 | 0.00 | 1.54 | 83.93 |
| FC-PHEV-hydrogen Potato Peels+electricity | 0.77 | 45.95 | 0.55 | 0.00 | 0.42 | 25.36 |

Figure 5 shows the energy results for WTW and Figure 6 the $CO_2$ emissions WTW results for the fuels and technologies analyzed.

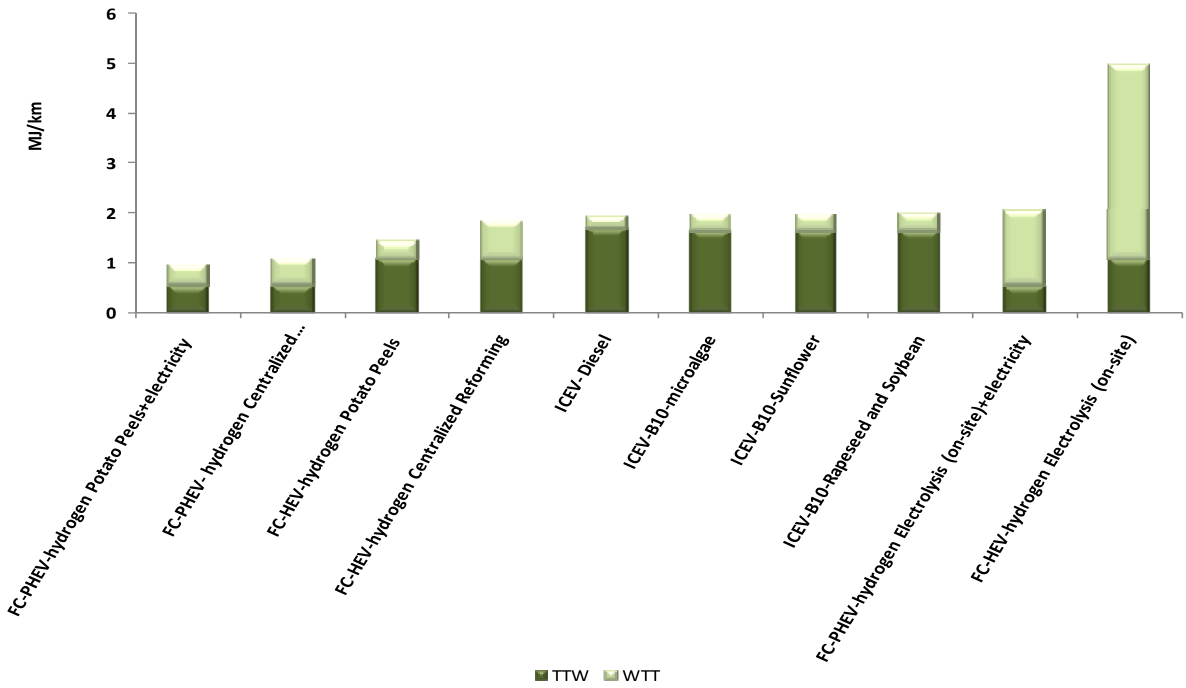



**Figure 5: Energy consumption for WTW of hydrogen, diesel and biodiesel fuels and technologies analyzed.**

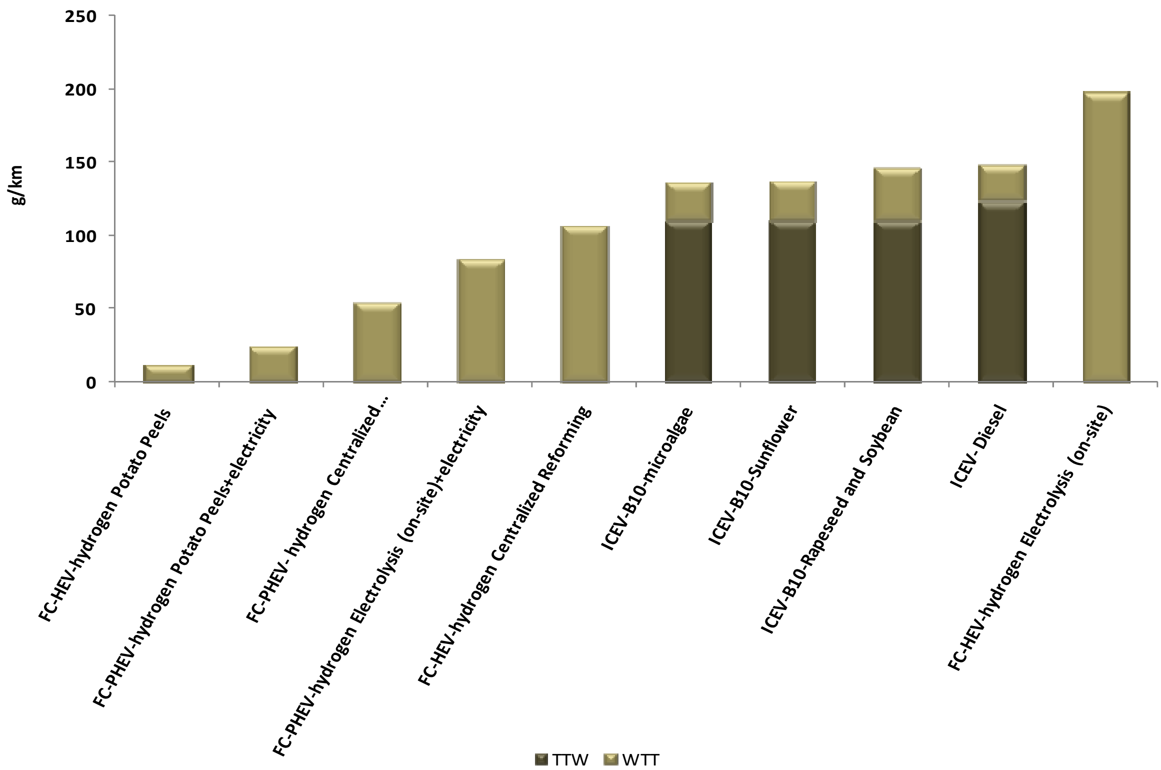



**Figure 6: WTW $CO_2$ emissions for WTW of hydrogen, diesel and biodiesel fuels and technologies analyzed.**

An extensive fuel life cycle was assessed for conventional diesel and fuel cell vehicle technologies. The main focus was on hydrogen production pathways, namely, trough hydrolyses and fermentation of potato peels.

Main findings for WTT part of fuel life cycle: the required energy resulting from sunflower, rapeseed/soybean, microalgae and diesel are respectively 0.77, 0.99, 0.75 and 0.16 $MJ/MJ_{fuel}$. The required $CO_2$ emissions resulting are respectively 39, 90, 35 and 14 g/ $MJ_{fuel}$. For hydrogen the respective values are 0.33 $MJ/MJ_{fuel}$ and 8.05 g/ $MJ_{fuel}$. No credits for $CO_2$ capture from crops/algae/oil were considered. The total energy consumption of the WTT pathways doesn't include the energy content of the produced fuel.

Main findings for the entire WTW fuel life cycle: with the exception of the electrolysis pathway, fuel cell vehicles presented the lowest values regarding energy consumption and $CO_2$ emissions. Besides potato peels pathway has balanced values for the energy consumption with centralized reforming, but both with the lowest values, for the CO2 emissions the potato peels have the lowest values (1-1.5 MJ/km and 13-25 g/km).

**Acknowledgements**

Thanks are due to the Fundação para a Ciência e Tecnologia for the PhD financial support (SFRH/BD/60373/2009).

The authors would like to acknowledge FCT-Fundação para a Ciência e Tecnologia (National Science and Technology Foundation) through the project Power demand estimation and power system impacts resulting of fleet penetration of electric/plug-in vehicles (MIT-Pt/SES-GI/0008/2008).

**References**

[1] DGEG – Caracterização energética nacional, 2007;

[2] Greenhouse gas emission trends and projections in Europe 2008, EEA Report Nº 5/2008;

[3] Zurawski, D., Meyer, M. and Stegmann, R., "Fermentation Production of biohydrogen from biowaste using digested sewage sludge as inoculums",Tehth International Waste Management and Landfill Symposium, Italy, Sardinia 2005;

[4] Kotay, Shireen Meher, Das, Debabrata, "BioHydrogen as a renewable energy resource – Prospects and potentials", International Journal of Hydrogen Energy, 33, 258-263, 2008;

[5] Danko, Anthony S., Abreu, Ângela A., Alves, M. Madalena, " The effect of paper waste and food waste on biohydrogen production at mesophilic temperatures in batch reactors", Book of Abstracts of the 10th International Chemical and Biologic Engineering Conference – CHEMPOR 2008;

[6] Nandi, R., Sengupta, S., "Microbial production of hydrogen: An overview", Critical. Rev. Microbiol. 24 (1), 61-84, 1998;

[7] Marano, John J., Rogers, Shelby, "Process System Optimization for Life Cycle Improvement", Environmental Progress, 18, 4, 267-272, 1999;

[8] Koreneos, C., Dompros, A., Roumbas, G., Moussiopoulos, “Life cycle assessment of hydrogen fuel production processes”, International Journal of Hydrogen Energy, 29, 1443-1450, 2004;

[9] Djomo, Sylvestre Njakou, Humbert, Sebastean, Blumberga, Dagnija, “Life cycle assessment of hydrogen produced from potato steam peels”, International Journal of Hydrogen Energy, 33, 3067-3072, 2008;

[10] General Motors, “Well-to-Wheels analysis of future automotive fuels and powertrains in the European context”, WELL-TO-TANK Report, Version 2b, May 2006;

[11] INE, Instituto Nacional de Estatística;

[12] Fernandes, Anderson Felicori, Pereira, Joelma, Germani , Rogério, Oiano-Neto, João, “Efeito da substituição parcial da farinha de trigo por farinha de casca de batata (Solanum Tuberosum Lineu)”, Ciência e Tecnologia de Alimentos, Campinas, 28(Supl.), 56-65, 2008;

[13] Baptis, Patrícia, Silva, Carla, Farias, Tiago, “ Biodiesel fuel pathways for the portuguese road transportation sector”, Smart Energy Strategies, Meeting the Climate Change Challenge, Switzerland, 2008;

[14] Baptista P, Tomás, M., Silva, C. Hybrid plug-in fuel cell vehicles market penetration scenarios. International Journal of Hydrogen Energy, xxx, 1-7, 2010.

# Extensive Analysis of Hydrogen Costs

**D.M. Guinea, D. Martín, M.C. García-Alegre, D. Guinea**, Instituto de Automática Industrial, Consejo Superior de Investigaciones Científicas, 28500 Arganda, Madrid, Spain
**W.E. Agila**, Departamento I+D+i, Acciona Infraestructuras, C/Valportillo II, 8. 28108 Alcobendas, Madrid, Spain

**Abstract**

Cost is a key issue in the spreading of any technology. In this work, the cost of hydrogen is analyzed and determined, for hydrogen obtained by electrolysis. Different contributing partial costs are taken into account to calculate the hydrogen final cost, such as energy and electrolyzers taxes. Energy cost data is taken from official URLs, while electrolyzer costs are obtained from commercial companies. The analysis is accomplished under different hypothesis, and for different countries: Germany, France, Austria, Switzerland, Spain and the Canadian region of Ontario.

Finally, the obtained costs are compared to those of the most used fossil fuels, both in the automotive industry (gasoline and diesel) and in the residential sector (butane, coal, town gas and wood), and the possibilities of hydrogen competing against fuels are discussed. According to this work, in the automotive industry, even neglecting subsidies, hydrogen can compete with fossil fuels. Hydrogen can also compete with gaseous domestic fuels. Electrolyzer prices were found to have the highest influence on hydrogen prices.

## 1 Introduction

### 1.1 Hydrogen costs

Fuel cell costs have been widely analyzed, but in order to have affordable hydrogen systems, both the fuel cell and the hydrogen consumption must have, for end users, competitive prices: similar or lower than those of current motors and fossil fuels.

Depending on the method used for hydrogen obtaining, different costs of infrastructure, energy and raw materials should be considered. Hydrogen production by electrolysis is an interesting option for the long term, because it does not need fossil fuels and the energy needed by the electrolysis can be obtained from renewable sources.

The global hydrogen cost as an addition of several costs has already been done for some areas, such as the West Danish area [1].

### 1.2 Energy costs

Unlike most of the products, electric power costs are not constant. They depend significantly on time [2]. Depending on the ratio between the required energy and the rate of energy obtaining (power), the energy would be bought only in the times when it is cheaper, or should be bought in every time. This depends basically on the power of the hydrogen generation system (in our case, an electrolyzer), which depends mainly on its costs: if the cost per unit of power is high, low powers will be used, in order to optimize the global cost.

### 1.3 Electrolyzer costs

Electrolyzer costs are significantly dependant on the technology. The large majority of current commercial electrolyzers are alkaline or PEM. Alkaline electrolyzers are considered the most commercially affordable option for hydrogen production [3], due to their lower costs. For this electrolyzer type, the main costs to be considered are the electrolyzer itself and power costs [4]. Although water is used in large quantities, its costs are not significant for the cost of the produced hydrogen. Their durability is estimated in 15-20 years.

## 2 Data

### 2.1 Electric energy prices

The prices of the electric energy were taken from official webpages. Five sets of data were obtained and used later for the calculations: Germany-Austria, France, Switzerland, Spain and Ontario.

The prices for Germany, France, Austria and Switzerland were taken from the European Energy Exchange (EEX) webpage [5]. Three sets of data were obtained from this page: one for Germany and Austria, another for France and a final one for Switzerland. The Spanish prices were obtained from the webpage of the Spanish Energy Commission [6]. The prices from Ontario were found on the IESO (Independent Electricity System Operator) webpage [7].

### 2.2 Electrolyzer prices

Most electrolyzer prices are given after demand on the electrolyzer. However, some studies summarize these costs. On one of them, the cheapest industrial electrolyzers are found to be about 100.000 $ per kg/h. Assuming a 60% efficiency at nominal conditions, that is approximately 1.300.000 €/MW [8]. Literature costs were lower, but this is often associated to mass production costs, which are not available yet.

### 2.3 Fuel cell data

The possibility of adding a fuel cell to the system was considered. This fuel cell may be useful for selling electricity back to the electric system, obtaining profits and reducing hydrogen costs. The fuel cell cost and durability were considered to be 55 €/kW and 2000 hours [9].

## 3 Procedure

### 3.1 Assumptions

Several assumptions were taken for this work:

- A system formed by a fuel cell and an electrolyzer is considered. The electrolyzer is used for obtaining hydrogen. The fuel cell is considered to sell energy back to the electric market, in case the price of the electricity in the market is above the price of the hydrogen needed to produce it.

- The performances of system electrolyzer and fuel cell are linear with the current and, therefore, with the hydrogen consumption. This is not exact, because the performance changes more for low currents than for high current, but is an acceptable hypothesis, since both the electrolyzer and the fuel cell would work mostly on the linear region.

### 3.2 System behavior

For each situation a given price of the hydrogen was calculated or assumed. For each hour of the year a decision was taken about electrolyzing water, consuming hydrogen or neither of them. The following cases were considered:

- If the hourly electricity price divided by the hydrogen price is below the maximum efficiency of the electrolyzer, hydrogen was produced by electrolysis. Hydrogen was produced with an efficiency that was the average between this price ratio and the maximum efficiency, with the limit of the minimum efficiency of the electrolyzer (the hydrogen production efficiency could not be below that minimum). This average optimizes the total profit of the hydrogen production, which is proportional to the hydrogen production and also to the difference between the production efficiency and the price ratio (which is proportional to the difference between incomes and hydrogen production costs).

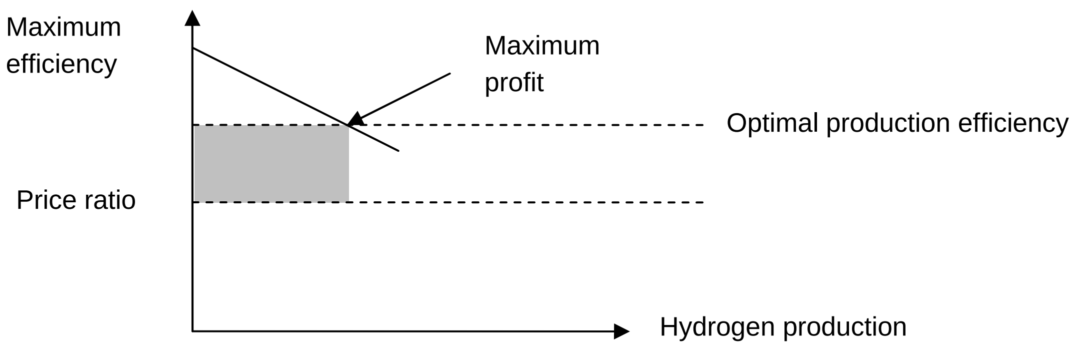



**Figure 1: Optimal point for hydrogen production. The profit is proportional to the grey area: it is proportional to the hydrogen production and to the difference between the production efficiency and the price ratio.**

- If a fuel cell is considered and the hydrogen price divided by the hourly electricity price is below the maximum efficiency of the fuel cell, hydrogen is consumed by the fuel cell to produce power. To maximize profits, the fuel cell efficiency is the average between the maximum efficiency and the previously mentioned price ratio.
- If none of the two previous cases is happening, the system does not consume or produce hydrogen.

### 3.3 Calculation of the total hydrogen costs

To calculate the total hydrogen cost, four different components were considered: the electricity price, the electrolyzer price, the fuel cell price and the net profit of the facility due to the energy interchange with the electric market. The last component was negative: this energy interchange profit could absorb part of the electrolyzer costs, decreasing the part of this cost that should be charged to the hydrogen price. The fuel cell price is optional: it was only added if it produced a decrease on the total price (increasing the negative contribution of the net profit).

Both the electricity price and the fuel cell price were optimized. Higher electricity price imply that hydrogen is produced in more hours and consumed in less, so the net production of hydrogen increases, decreasing the electrolyzer costs per unit of produced hydrogen. Higher fuel cell prices and powers cause a higher profit through interchange with the electric market. In both cases, the trade-off between both variables was found.

## 4 Results

The results were first calculated for a base case, where the costs and the maximum and minimum efficiencies were assumed to have a certain value. Later, a sensitivity analysis is performed to study the effect of changes in these variables.

### 4.1 Base case

In the base case, the minimum and maximum electrolyzer efficiencies were assumed to be 0.6 and 0.8. The latter one belongs with an approximate voltage of 1.5 V, which is approximately the minimum current at which alkaline electrolyzers begin to produce a significant amount of hydrogen. The minimum electrolyzer efficiency belongs with a voltage of 2 V, which is approximately in the middle of the electrolyzer nominal-voltage range.

A maximum fuel cell efficiency of 0.7 is considered, which corresponds with an approximate voltage of 0.85 V. Although fuel cell voltages can usually be higher, this voltage is close to the intersection of the extrapolation of the linear region with the zero-current axis, so it is useful for modeling this linear region.

The price results are shown in Figure 2:

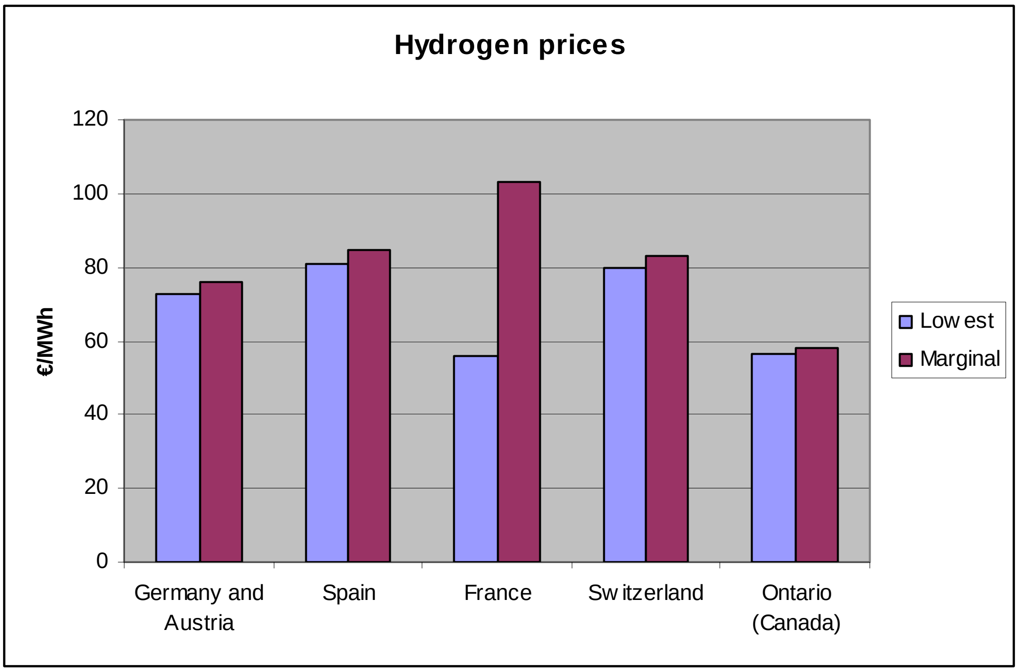



**Figure 2: Lowest and marginal hydrogen prices for different countries. The lowest price is the minimum profitable price. The marginal price is the price that the system internally gives to the hydrogen, in order to electrolyze or not.**

The lowest and marginal hydrogen prices are quite close for most of the countries. Excluding France, the difference is always below 6% of the marginal cost. The final base cost of hydrogen may be closer to the lowest or the marginal cost, depending on the competence of the market. Excluding France, the lowest cost is below the marginal cost because most of the hydrogen is produced with a cost below the marginal one. The reduction of the electrolyzer costs per unit of produced hydrogen may justify producing hydrogen, in some cases, with a cost slightly higher than the price at which it will be sold, in order to increase hydrogen production.

In the case of France, there are significant differences between both prices because the hydrogen energy storage system may be profitable by itself (reselling later the energy to the electric system with a fuel cell). If the ratio between the yearly income and the yearly outcome of the system is maximized, the marginal cost of the hydrogen would be about 103.1 €/MWh (and 256.2 MW of fuel cell would be used per MW of electrolyzer). However, hydrogen energy storage systems can be profitable with a marginal cost as low as 55.83 €/MWh (and 13.97 MW of fuel cell per MW of electrolyzer).

For all the other countries but France, the addition of a fuel cell to the system, even if it was small, was not profitable.

All the hydrogen prices are between 55 €/MWh and 104 €/MWh. If these values are calculated per unit of mass or per unit of weight, the results would be between 2.2 and 4.1 €/kg or between 0.19 and 0.37 €/Nm$^3$, respectively. The prices could be also compared with those of current fuels for automotive applications. From each gasoline liter approximately 2.4 kWh of mechanical energy are obtained and for each diesel liter, approximately 3.2 kWh [10]. Assuming a fuel cell plus electric motor system to power a car, a 0.5 average fuel cell efficiency and a 0.9 average motor efficiency, each MWh of hydrogen would yield 450 kWh. Therefore, the hydrogen base prices (before taxes and commercial benefits) are between 0.29 € and 0.55 € per equivalent to a gasoline liter and between 0.39 € and 0.74 € per equivalent to a diesel liter. This ranges are approximately centered in the current values of gasoline and diesel: which were 0.44 €/l and 0.55 €/l in 2008 [11] (the latest available information at the time when this work was done).

Wood has costs about 0.12 €/kg and a heating power about 5 kWh/kg, which makes a cost per unit of energy of 0.024 €/kWh, which is 24 €/MWh. Coal costs about 0.10 €/kg and has a heating power of approximately 9 kWh/kg, so the cost per unit of energy is 0.011 €/kWh, 11 €/MWh. Butane prices are about 0.94 €/kg and its heating power is about 13 kWh/kg, which yields a cost per unit of energy of 0.072 €/MWh, which is 72 €/MWh. The cost of town gas is about 0.07 €/kWh, 70 €/MWh.

## 4.2 Sensitivity analysis

A sensitivity analysis was performed, changing different variables to study their effect on the hydrogen cost. The most influencing variables was the electrolyzer cost. Figure 3 shows its influence:

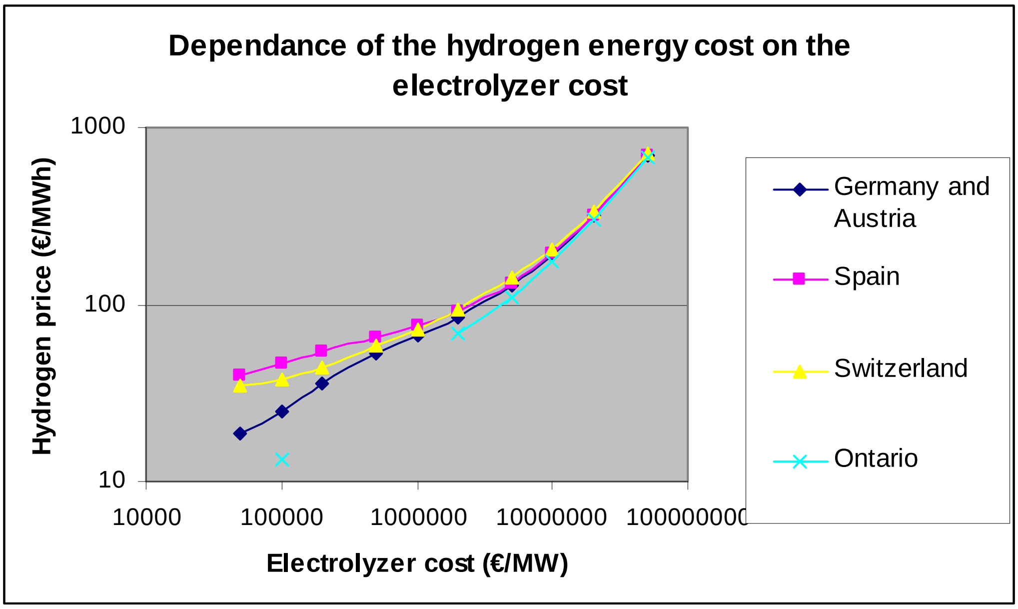



**Figure 3: Influence of the electrolyzer cost on the hydrogen cost.**

The electrolyzer costs influence clearly the hydrogen cost. For low cost, this influence is smaller and there are significant differences on the hydrogen costs among countries, as most of the hydrogen costs depends on the energy. For high electrolyzer costs, the influence is clear and the hydrogen costs among countries are close in relative terms.

The dependence of hydrogen costs on other variables was also studied. Fuel cell costs only influenced costs in France and Canada, where high electricity prices during some hours make fuel-cell energy generation profitable. If fuel cell costs are low, hydrogen generation costs may decrease in these countries to 38 €/mWh in Ontario and 49 €/Mwh in France. However, if fuel cell costs are high, energy generation from the fuel cell is no longer profitable, and hydrogen prices climb to 76 €/mWh in France and 56 €/Mwh in Ontario.

A change of the maximum electrolizer efficiency from 70% to 90% had an effect on the hydrogen costs between 2% and 5%. A change of the minimum electrolyzer efficiency from 50% to 70% changed the hydrogen costs about 25%. This is probably attributed to a higher hydrogen production (the ratio between maximum production and cost is being changed). In both cases, logically, higher efficiencies resulted in lower costs. The effect of the fuel cell performance was studied for France, where the addition of a fuel cell was profitable. A change from 60% to 80% of the fuel cell efficiency changed the minimum hydrogen price in about 10%.

## 5 Conclusions

The main conclusions that can be extracted from the current work are:

- Under the base case, the base cost of hydrogen energy for automotive applications would be equivalent to that of current fuels.
- For domestic applications, hydrogen can only compete with gaseous fuels (such as butane and town gas), which have similar costs. Solid fuels (such as wood and coal) have significantly lower costs.
- Electrolyzer cost is the variable with a highest influence on hydrogen costs. This influence is specially significant for high electrolyzer costs.
- In some countries, like France, hydrogen systems could already be profitable interchanging energy with the electric system, due to the very high energy prices during some hours.

## References


[1] C. Jorgensen and S. Ropenus. Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration. International Journal of Hydrogen Energy.Volume 33, issue 20. October 2008. Pages 5335-5344.

[2] F.C. Schweppe, M.C. Caramanis, R.D. Tabors and R.E. Bohn. Spot pricing of electricity. Kluwer Academic Publishers. ISBN: 0-89838-260-2. Boston/ Dordrecht/ London.

[3] J.D. Holladay, J. Hu, D.L. King and Y.Wang. *An overview of hydrogen production technologies*. Catalysis Today. Volume 139, issue 4. January 2009. Pages 244-260.

[4] J.M. Merino Azcárraga. *Hidrógeno y energías renovables. Nuevas tecnologías para la sostenibilidad*. Edited by Tecnalia. ISBN: 84-609-8899-6.

[5] http://www.eex.com/en/. European Energy Exchange: EEX Home Page. Observed at 05/03/2010.

[6] http://www.cne.es/cne/contenido.jsp?id_nodo=338&&&keyword=&auditoria=F. CNE – Comisión Nacional de Energía – Precio Final Medio y Energía. Observed in 05/03/2010.

[7] http://www.ieso.ca/imoweb/marketdata/marketData.asp. Market Data. “Hourly Ontario Energy Price (HOEP)” file in the “Download Historical Data Files” section. Observed in 05/03/2010.

[8] J.X. Weinert, T.E. Lipman. *An Assessment of the Near-Term Costs of Hydrogen Refueling Stations and Station Components*. January 2006. UCD-ITS-RR-06-03. Hydrogen Pathways Program. Institute of Transportation Studies. University of California – Davis. http://www.its.ucdavis.edu/publication.html.

[9] Department of Energy. *Fuel Cell School Buses*. Report to Congress. December 2008.

[10] Wikipedia. *Diesel* engine. http://en.wikipedia.org/wiki/Diesel_engine. Observed at 11/03/2010.

[11] Comisión Nacional de Energía (Spanish Nacional Energy Comission). Dirección de Petróleo. *Informe de supervisión sobre la evolución del precio de venta al público de la gasolina 95 y del gasóleo de automoción en España durante 2008*. May 7th 2009.

# An Exergetic Life Cycle Assessment for Improving Hydrogen Production by Steam Methane Reforming

**Noureddine Hajjaji, Ammar Houas**, Equipe de Catalyse et Environnement , Ecole Nationale d'Ingénieurs de Gabès, Université de Gabès, Tunisie
**Marie Noëlle Pons, Viviane Ranaudin**, Laboratoire Réactions et Génie des procédés – CNRS, Nancy-Université, France

Hydrogen is expected to play a significant role in the future energy system. An efficient production of hydrogen with minimum cost and in an environmentally acceptable way is crucial for the development of our hydrogen-based economy. As recent technological progress has made hydrogen a realistic long-term energy option with little or no pollution, the developments of new methods for hydrogen production and the improvement of conventional technology are of a permanent importance. However, on a shorter time perspective, there will be a transitory period, during which large-scale hydrogen production will be based on optimization and improvement of current technologies. Actually, Steam Methane Reforming (SMR) is one of the most important and commonly used processes of hydrogen production. The SMR technology is the oldest, the cheapest, and the most widely used.

Recent years have seen an upsurge of interest in life cycle assessment (LCA) as a tool for evaluation, with a cradle to grave approach, of potential environmental impacts of a product, process, or activity. During the past decade several researchers have tried to enhance LCA methods by considering exergy rather than or in conjunction with energy flows. Such an extension of LCA is referred to as exergetic life cycle assessment (ELCA). Exergy is defined as the maximum amount of work that can obtained when a thermodynamic system or flow (e.g., matter, heat, work) is brought into equilibrium with a reference environment. ELCA determines the depletion of natural resources, while the other environmental effects are calculated with the LCA.

The purpose of this study is to demonstrate how the results of an Exergetic Life Cycle Assessment (ELCA) can be used to improve the performances of an SMR process. The methodology opted in this work contain three main steps.

In the first step, the SMR process is simulated using Aspen Plus™ software. The thermodynamic data and phase behavior predictions of the material stream are achieved using the Soave-Redlich-Kwong equation of state and the component list was restricted to $CH_4$, $O_2$, $N_2$, $H_2O$, CO, $H_2$ and $CO_2$. The SMR process studied consists of four sections: natural gas pretreatment, synthesis gas generation, water gas shift and gas purification.

The first section, which is natural gas pretreatment, consists of removing the impurities present in the natural-gas feedstock to avoid poisoning the catalysts.

In the second section called the reforming ((1) and (2)), natural gas - steam mixture is catalytically converted to hydrogen, carbon monoxide and carbon dioxide. The reforming reaction is highly endothermic and a large amount of heat is provided by external burners.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H^0_{298} = 206 \text{ kJ.mol}^{-1} \qquad (1)$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \qquad \Delta H^0_{298} = 165\ kJ.mol^{-1} \qquad (2)$$

These reactions are typically carried out at a temperature of 800–1000°C and a pressure of 14-20 atm over a nickel based catalyst.

The syngas exiting the reformer is passed through a water–gas shift (WGS) reactor that converts the CO in the syngas to $CO_2$ and $H_2$ using the available $H_2O$ in the syngas or from additional $H_2O$ added to the system. Herein, the following reaction occurs:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = -41\ kJ.mol^{-1} \qquad (3)$$

In practice, the shift reaction takes place over two reactors that operate between 200- 400 °C and 125–180 °C, respectively.

The last section is the purification of hydrogen. It consist of producing high end stream $H_2$ purity (>99%).

In the second step an energetic and exergetic analyses are performed for the SMR process as following: (1) Determination of the process stream exergy (physical, chemical and mixing exergies) (2) Performing the exergy balance for the process element. (3) Calculation of the process energetic and exergetic efficiencies.

The results indicate that the thermal and the exergetic efficiencies of the SMR process are respectively 70% and 65.5%. It shows that 26.67% of exergy reaching the process are destroyed due to the thermodynamic imperfections. The main part of the destroyed exergy is located in the reformer with à contribution of 65.81% of the whole process destroyed exergy. The exhaust exergy represents 7.86% of process inlet exergy, this attributed to the smoke physical exergy. The improvement of the process energetic and exergetic performances will be by reducing its exhaust exergy. This is performed by incorporating, in the original process, a third economizer for a smoke calories recovery. Consequently a new process is build (SMR2).

In the third step, the processes performances comparison is achieved using ELCA approach. The life cycle assessment is done according to the ISO 14040 series. The LCA process is a systematic approach that consists of four stages: goal definition and scoping, inventory analysis, impact assessment and interpretation. The SimaPro LCA Version 7.1 software's Eco-indicator 99 method is used to investigate the following three environmental impact categories: human health, ecosystem quality and resources. The ultimate goal of this ELCA is to compare the environmental impacts of two SMR processes for hydrogen production. The functional unit is one mole of hydrogen produced by each process. The construction and dismantlement of SMR equipments and the catalyst production are assumed equivalent for each process. Therefore they are neglected in this study. The systems have three stages:

- Hydrogen production plant.
- Production and distribution of natural gas.
- Production and distribution of electricity.

The required data to conduct the impact analysis for production and distribution of natural gas and electricity are taken from the SimaPro 7.1 database, while the SMR operating parameters are obtained by using Aspen Plus™ software.

The results obtained indicate that by incorporating a new heat exchanger in the original process (SMR1) we obtain multiple benefits:

- The thermal and the exergetic efficiencies of the new process are respectively 74% and 69.1%. However, for the original process they are 70% and 65.5%.
- The un-used exergy is reduced by 9.3% from 125.9 to 114.2 kJ per mole of $H_2$ produced. One mole of methane in the new process is more hydrogen productive. It produces 2.48 mole $H_2$ against 2.35 mole $H_2$ for the original process.
- The figure 1 shows a reduction in all the process categories impacts. Thus we observe theses reductions: 5% in human health indicator, 3% in ecosystem quality and 5% in resources.
- The figure 2 shows 5.2% as reduction in the process' single score.

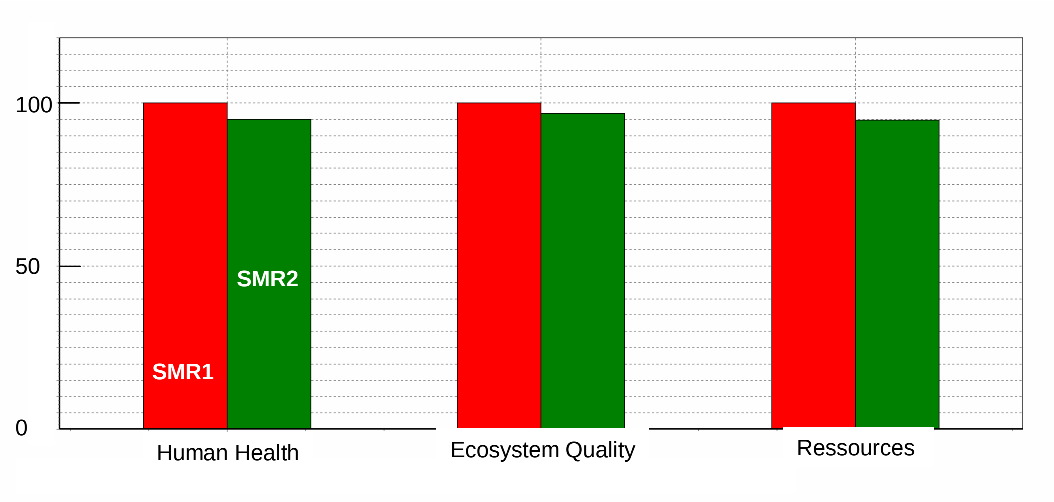



**Figure 1: SMR damage assessment result in bar chart (EcoIndicator 99).**

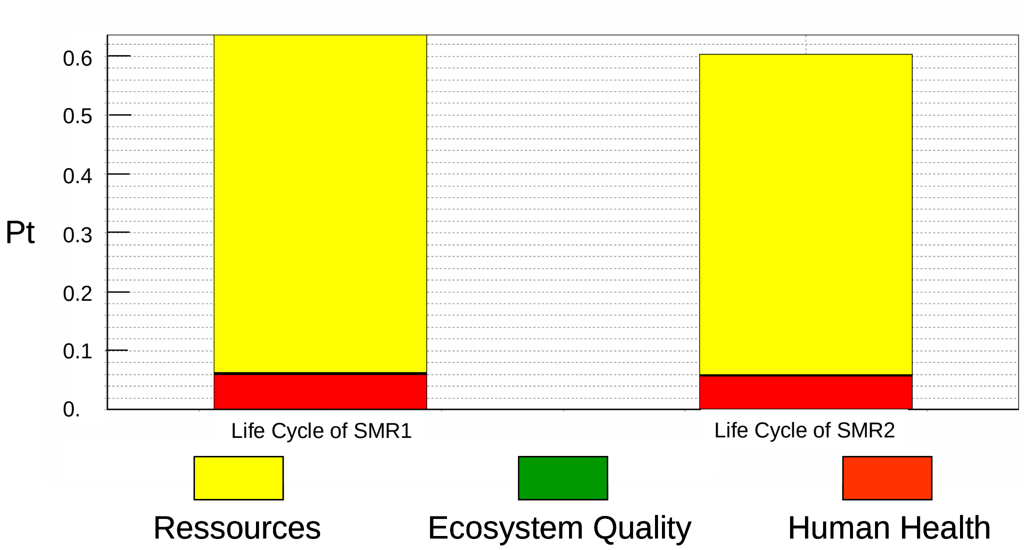



**Figure 2: SMR Single score in bar chart (EcoIndicator 99).**

## SA Strategic Analyses

SA.1 Research & Development Targets and Priorities

SA.2 Life-Cycle Assessment and Economic Impact

SA.3 Socio-Economic Studies

SA.4 Education and Public Awareness

SA.5 Market Introduction

SA.7 Regional Activities

SA.8 The Zero Regio Project

# Strategic and Socioeconomic Studies in Hydrogen Energy

David Hart

**Abstract**

The introduction of hydrogen as an energy carrier is not only a technology and science challenge, also requiring the engagement of many socioeconomic disciplines. Analysing the conventional economic implications of different potential manifestations of a hydrogen economy is important, but so is the inclusion of externality assessment. New business models and financing schemes need to be developed to help us understand the balance between short and long term costs and rewards, and between private and social impacts. The behaviour and perceptions of different actors in any possible transition and future have a strong bearing on whether or not it can ever reach fruition, and methods such as actor and transition analysis can assist in their evaluation. All of these disciplines and more must be linked with the science, technology and engineering aspects of hydrogen energy deployment in order to assess its potential and derive appropriate methods of support.

# Building a Hydrogen Refuelling Infrastructure in the Netherlands: Influencing Factors from the Car Drivers' Perspective

**Ingo Bunzeck**, **Julia Backhaus**, Policy Studies, Energy research Centre of the Netherlands (ECN), The Netherlands,
**Bart Hoevenaars**, Hydrogen and Clean Fossil Fuels, Energy research Centre of the Netherlands (ECN), The Netherlands

## 1 Introduction

The introduction of hydrogen as a new, alternative fuel bears numerous challenges, one of which is the development of a refuelling infrastructure. The THRIVE ('Towards a Hydrogen Infrastructure for Vehicles') project aims to provide possible developmental routes and technological options for a hydrogen refuelling infrastructure in the Netherlands[1]. The model builds on the assumption that the commercial roll-out of hydrogen vehicles and the necessary infrastructure will take off within the coming decade. By making this assumption, research can focus on identification of relevant stakeholders, cost analyses, testing of technological options and actions to be taken for a successful introduction of hydrogen as alternative transport fuel for passenger cars.

The modelling approach at the core of the project allows testing different roll-out scenarios for the 15-20 years after commercial introduction. The modelling efforts have been underpinned by socio-economic research, such as supporting policy measures and consumer behaviour with respect to the introduction of innovative technologies.

This paper focuses on relevant behavioural aspects, in particular on car drivers' current refuelling behaviour and its implications for the development and layout of a hydrogen refuelling infrastructure. 'Refuelling behaviour' is in this context concerned with the temporal and spatial dimensions of decisions and actions car drivers take when wanting and/or needing to fill up the fuel tank of their car.

Previous research concerning refuelling behaviour provides important insights which are reviewed in more detail in the following chapter. The importance of matching the usability of a new alternative fuel to the current use of incumbent fuels called for an analysis of current refuelling behaviour of Dutch car drivers for the THRIVE project. The need for country-specific and up-to-date results is particularly relevant as existing research on refuelling behaviour mostly focuses on the US and dates from the 1980s. Drivers' refuelling behaviour varies between countries as it depends on a country's size, road infrastructure, dispersion of cities, refuelling infrastructure (i.e. station network), and cultural norms and values related to driving. US cities sprawl and often lie far apart. In the Netherlands, the population density is much higher and cities are located close to one another.

---

[1] The THRIVE consortium consists of ECN and TNO as research institutes as well as Shell and Linde Benelux representing industry.

The present analysis therefore aims to provide new insights on Dutch car drivers' refuelling behaviour. Another objective of this analysis is gaining an understanding of the relation of fuel availability and people's willingness to use a particular fuel. Fuel availability in this context refers to the number of stations per zipcode-area offering a particular fuel. This 'station coverage' is set in relation to people's 'willingness to switch', namely their readiness to start using a different fuel than the one they are currently driving on. In particular, it aims to answer the questions: When and where during a trip do Dutch car drivers decide to refuel their car? And what station coverage of an alternative fuel do people consider acceptable when deciding to buy an alternative fuel car. By means of an online survey, Dutch car drivers were presented with a number of questions. The quantitative analysis of their answers is discussed in this paper.

The paper is structured in four sections. Following this introduction, section 2 reviews previous research outcomes on refuelling behaviour and strategic infrastructure development for an alternative fuel. The same section describes in more detail the survey on refuelling behaviour of Dutch car drivers carried out in the framework of the THRIVE project the results of which will be presented in section 3. Conclusions can be found in section 4.

## 2 Background

### 2.1 Previous research

The build-up of refuelling infrastructure for an alternative fuel has already received attention by the research community for a couple of decades. Of particular interest are the station coverage required to make a successful introduction of a new fuel [1], and drivers' willingness to make a detour in order to reach a station offering the fuel they need. Both these issues are firmly rooted in drivers' current refuelling habits. Although not all studies were concerned with the same alternative fuel, general consensus is that the successful introduction of alternative fuel vehicles (AFVs) strongly depends on (perceived) fuel availability. Sperling and Kitamura [2] enquired into decisive factors for people considering the purchase of an AFV and conducted a large survey among Californian drivers. They conclude that perceived fuel availability plays an important role in the purchasing decision for a car. Interestingly, a spatially well-planned refuelling infrastructure with high predictability of the location of stations offering a certain fuel can well compensate for overall lower availability. Furthermore, Sperling and Kitamura analysed the relation of fuel price and the necessity to make a detour in case of lower fuel availability. Generally, drivers are ready to make a detour if the additional fuel used to detour is offset by means of a lower fuel price.

Research by the same authors [3] reveals behavioural patterns or habits important for the strategic planning of an alternative refuelling infrastructure. Their data show that most people refuel in areas they are rather familiar with, e.g. close to their home or close to their work. Furthermore, people frequently refuel on their daily travel, e.g. the commute between home and work, rather than on trips they do less often, e.g. for shopping. However, there are also drivers who make special tours only to refuel their car. The results of these two studies point to the importance of strategic planning of an alternative refuelling infrastructure with a focus on main commuting routes (along highways or larger roads) in order to meet drivers' most common demands and to compensate for the (initially) lower availability of a new fuel.

More recent research – also based on American data – comes to similar conclusions as the two publications reviewed above. Melaina and Bremson argue that an alternative refuelling infrastructure is best initiated in urban agglomerations, as it requires less capital investment and meets the possibly more frequent need to refuel caused by the lower range of some AFVs [4]. However, the current station coverage of one in every 3.3 minutes drive time that the authors found in urban areas with a population density above 250 people per square mile[2] is deemed unnecessary. They conclude that a density of station offering an alternative fuel could be 33% lower than current coverage and still supply sufficient availability[3].

Apart from research mostly focusing on the US, also some data are available for the Netherlands. A research carried out by Van Amelsfoort [5] among 300 Dutch car drivers indicates that the distance of a refuelling station to the location of their work or home is for half of the respondents the second most important decision-making factor when choosing a station. Furthermore, 18% of the respondents are not ready to make a detour for an alternative fuel, while 37% is willing to drive an extra 2 km, 36% willing to drive an extra 5 km, and 10% an extra 10 km. The lack of detailed data from the Netherlands and the US-bias of available literature on refuelling behaviour called for a larger survey among Dutch drivers.

### 2.2 THRIVE survey

In order to gain better insight into Dutch drivers' current refuelling behaviour and willingness to switch a survey was commissioned to TNS NIPO, a market research company based in Amsterdam. For the selection of a suitable sample, the TNS NIPO database of registered participants was searched and Dutch households owning at least one car were contacted. These households received a weblink that allowed respondents to enter their answers to the questions posed online. It was explicitly asked that the person using the car most frequently filled in the questionnaire.

The survey consisted of twelve questions. It was answered by 2,970 respondents. Most likely due to the fact that the most frequent driver of (one of) the household's car(s) was asked to reply to the questionnaire, most of the respondents were older than 40 (90%) and male (84%). Results of the statistical analysis of responses are presented in more detail and discussed in the following section.

## 3 Results

### 3.1 Introduction

The focus of the survey was to study the influence of the layout of a refuelling station grid on the willingness to switch to another fuel, assuming that there is a motivation to switch to more sustainable alternative vehicles. The scope of this study was not to answer the question why people would want to switch to a more sustainable energy source for their mobility. Typical

---

[2] Although they also found great variations in station coverage amongst different urban agglomerations with similar population densities.

[3] For more research available on sufficient station coverage, i.e. fuel availability, see e.g. Melania, M., McQueen, S., & Brinch, J. (2008) Refueling infrastructure for alternative fuel vehicles: Lessons learned for hydrogen, NREL/BK-560-43669

causes that may make consumers consider choosing for different, more sustainable and maybe more costly fuels can be, among others, climate change, oil depletion.

### 3.2 Refuelling behaviour

The first set of questions addressed habitual behaviour of drivers regarding the refuelling process, the location of the station they most frequently use and how much time it takes to get there. The most important results are elaborated in the following.

Nearly three quarters (74%) of all car drivers in the survey indicated that they refuel their car just after leaving home on the way to their destination or vice versa. This behaviour is not correlated with the driver's age. Almost 20% perform an extra trip solely for refuelling the car. This behaviour is correlated with age: the majority of people who makes an extra trip for refuelling is 55 years old or older. A plausible explanation for the large representation of this age-group could be the large representation of pensioners in this group that don't commute regularly and thus don't have the opportunity to refuel during habitual commutes. The survey indicates that it is rather unusual to refuel halfway for the majority of people. For long haul car-use however, it is reasonable to assume that refuelling far away from the point of departure and point of arrival is a logical choice.

The results of the survey show that the moment of refuelling is closely connected to the average drive time between home and the refuelling station. More than half (58%) of all drivers refuel their car within the first 5 minutes after departure. Another 25% refuels in between a time window of 5-10 minutes after departure. Summarised, this means that more than two-thirds of all drivers refuel their car within a maximum of 10 minutes after departure from a destination. Increased attention for the fuel gauge during the initial phase of a trip could be an explanation for the tendency to refuel shortly after departure but this has not been investigated further. The majority of the car drivers (59%) most frequently visits filling stations which are located in the built environment. Second most frequently visited are petrol stations which are located in between the place of departure and an access road to a highway (23%).

Drivers tend to choose their filling station for a number of reasons. In the survey, more than one answer was allowed. The large majority of the drivers (66%) throughout all age groups choose their stations on the basis of fuel price. The second most specified argument (35%) is the station's location along a driver's habitual route. Price and convenience are thus by far the two most important factors mentioned. Other factors that influence the choice of the refuelling station are the driver's participation in a bonus card system and brand-loyalty, each mentioned by 15% of the respondents.

### 3.3 Willingness to switch

The second set of questions in the survey specifically aimed at clarifying which preconditions are required to trigger a consumer to switch to sustainable automobility in terms of fuel availability. A consumer may be able to buy a hydrogen a biofuel powered vehicle but if the fuel-availability is below a certain threshold, the consumer may feels he runs the risk of regularly running empty on fuel. This of course may strongly reduce a consumer's will to switch to an alternative fuel vehicle.

More than one third of the survey participants (37%) indicated that it would be sufficient if the fuel is available at their most frequented filling station. However, the majority requested the alternative fuel to be available across the whole country, see Figure 1.

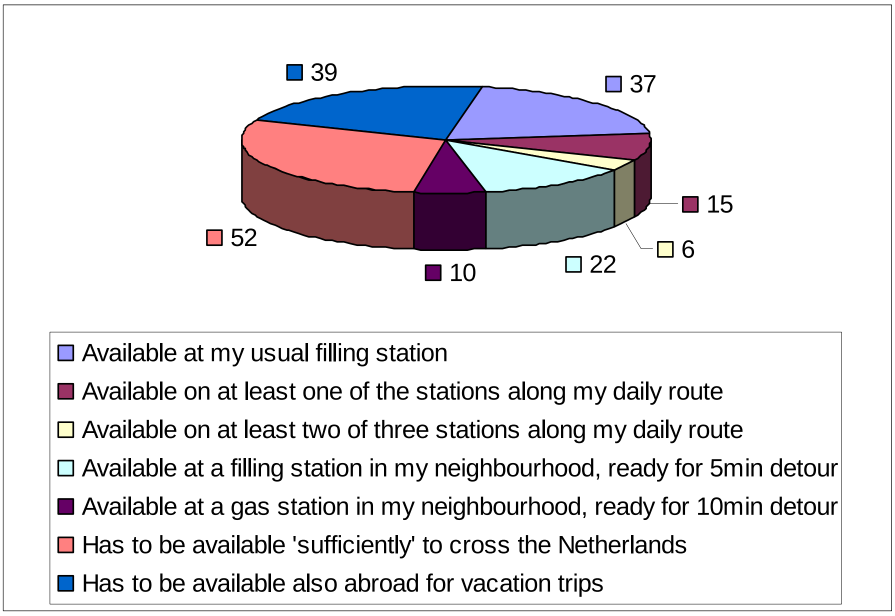



**Figure 1: Preconditions for fuel switching.**

Strikingly, the second most often chosen response was confirmative to a desired fuel availability abroad indicating that people like the possibility of being able to go on holidays abroad by car. Because of the structure of the questions used in the survey, it is however not possible to identify what set of correlations exists between multiple answers given by participants.

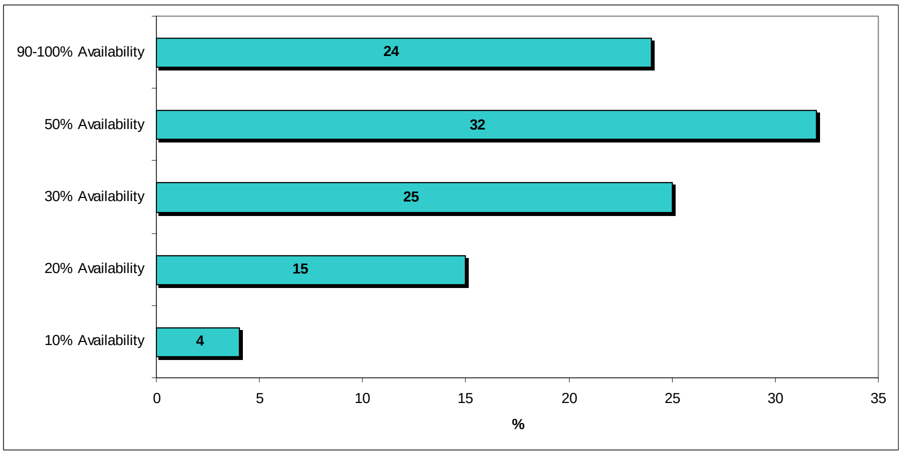



**Figure 2: Required alternative fuel station coverage.**

In the previously mentioned question, respondents could indicate that the alternative fuel has to be available sufficiently (i.e. at a number of random filling stations) to drive through the whole country of the Netherlands without fearing to run out of fuel. The participants who confirmed received a follow-up question to find out what exactly they define as sufficient station coverage. One quarter would require every third filling station of the existing fuel station grid to be equipped with the alternative fuel, while about one-third of the respondents (32%) requires the alternative fuel to be available at every second station. Taking into account the responses that would require low station coverage (1 out of 10 and 1 out of 5), almost 74% percent of the respondents would be satisfied if every second station offered the alternative fuel. Still, one quarter to the respondents' demands availability of fuel throughout the country with a higher response rate in the group of older people (>55 yrs.).

## 4 Conclusions

This study is based on a survey that was performed to chart the refuelling preferences of the Dutch population. The survey was performed to obtain insight in the initial requirements to realise a hydrogen refuelling infrastructure in the Netherlands. Very few results from studies to refuelling behaviour have been published before. An important comparable study was performed at the University of California by Kitamura and Sperling on refuelling behaviour among US citizens.

Comparison shows, that despite cultural differences between the USA and the Netherlands, a preference among drivers to refuel their car shortly after leaving a point of departure is a shared result of both our study and the work of Kitamura and Sperling. Furthermore, our study also confirmed the earlier findings of Kitamura and Sperling on the low willingness to make a detour to reach a refuelling station.

Further results of our study indicate that an initial infrastructure should be based on sufficient availability of hydrogen refuelling stations in the built environment and not just along highways. Drivers prefer to visit a refuelling station along their habitual route. Therefore, the highest acceptance of hydrogen-fuelled mobility among drivers could be achieved, as far as the influence of the refuelling infrastructure reaches, by upgrading existing, high turnover stations in the built environment. But local availability is not sufficient. Drivers require refuelling stations across the whole country and not only in key cities or regions. An initial hydrogen roll-out would therefore calls at least for a rudimentary coverage of the whole country and not just of key-cities or regions. It is a plausible assumption that drivers' demand for national refuelling grid coverage is based on people's fear to run out of fuel. However, it can also be argued that the widespread of availability of hydrogen refuelling points may be interpreted by consumers as a measure of success of an alternative fuel technology, as it may indicate that many more people throughout the whole country are choosing for the same alternative technology.

Furthermore, it was found in this study that Dutch car drivers appreciate the availability of an alternative fuel abroad. Again one could assume functional reasoning of the driver here: the international availability will facilitate international car-based travelling. Yet, the international availability of an alternative fuel refilling infrastructure may also be interpreted by a driver as an indication that that particular alternative fuel is internationally successfully adopted and thus a proven technology. This may be an additional factor facilitating people's switch to hydrogen-fuelled vehicles.

**Acknowledgements**

This report is part of the THRIVE project, a study on the possible build-up of a hydrogen infrastructure in the Netherlands. The study is jointly carried out by ECN, Shell, Linde and TNO. Within ECN, the units Clean Fossil Fuels and Policy Studies contribute to the project. THRIVE is financed by SenterNovem within the EOS-LT program under contract number EOSLT06025.

**References**

[1] Nicholas, M.A., Handy, S.I. & Sperling, D. Using geographic information systems to evaluate siting and networks of hydrogen stations. Transportation Research Record: Journal of the Transportation Research Board, (2004) No. 1880, Pp. 126-134

[2] Sperling D. & Kitamura R. (1986) Refueling and new fuels: an exploratory analysis. Transportation Research, 20(1), pp. 15-23

[3] Kitamura, R. & Sperling, D. Refueling behavior of automobile drivers. Transportation Research, 21A(3) (1986) Pp. 235-245

[4] Melaina, M. & Bremson, J. (2008) Refueling availability for alternative fuel vehicle markets: sufficient urban station coverage. Energy Policy, 36, pp. 3223-3231

[5] Van Amelsfoort, A. (2007) Weg vrij voor duurzame brandstoffen? Onderzoek naar bereidheid consumentom over te schakelen op duurzame brandstoffen. Groningen: EDReC en Wetenschapswinkel Economie & Bedrijfskunde RuG

# The Economic Feasibility of a Sustainable Hydrogen Economy

**J.J.C. Bruggink**, Institute for Environmental Studies, Vrije Universiteit, Amsterdam and Unit Policy Studies, Energy Research Centre of the Netherlands, Petten, The Netherlands
**H. Rösler**, Unit Policy Studies, Energy Research Centre of the Netherlands, Petten, The Netherlands

## 1 Introduction

*Feasibility of the hydrogen economy determined on battlefield for the car of the future*

The feasibility of the hydrogen economy is often viewed in terms of the early deployment of hydrogen vehicles, because the transportation sector plays a key role in solving problems of both energy security and climate change [1,2]. The promise of the hydrogen car has however faded by the arrival of an alternative that appears to offer far more hope for the immediate future. The hydrogen car hype of the late 1990's has been replaced by the electric car hype of the late 2000's. This change of perception can be traced to three disparate causes: first, the economic shock from a meteoric rise of the oil price in early 2008; secondly, the emerging promise of fast improvements in cost and performance of batteries; third, the increasing commercial alertness of European electricity companies looking for market expansion. Certainly, the battle for the car of the future is shaped by ambitious intentions and public hypes. But ultimately, the prospects for particular car concepts are a function of comparative technological performance on the one hand and uncertain economic factors on the other hand. The most important economic factors in this battle apart from vehicle costs are the development of world oil prices and fiscal regimes for vehicles and fuels including carbon taxes. The intention of this study is to develop a stylized picture of the battlefield for the car of the future, that captures the essence of competitive forces quantitatively and allows a broad picture of potential outcomes based on key assumptions regarding the combined effects of technological progress (reflected in vehicle costs), fuel price developments (of crude oil, electricity and hydrogen) and fiscal regimes (tax rates on vehicles and fuels including carbon prices). As main indicator of competitive fitness on the battlefield for the car of the future we will use the levelized costs per kilometre of competing vehicle concepts as experienced by car owners.

## 2 The Conventional Gasoline versus the Advanced Hydrogen Option

*Hydrogen vehicle costs are indeed crucial*

If you buy a gasoline ICE car of € 20000 today and drive 12000 km annually, your levelized vehicle costs would be about 27 c/km.[1] With oil prices at 80 $/barrel, your levelized fuel costs

[1] Assuming interest rate of 5%, economic lifetime of 10 years and current European fiscal regime

would be about 11 c/km.[2] Total costs amount to 38 c/km of which 70% vehicle related and 30% fuel related. Now suppose there is a hydrogen car manufacturer who is able to put a hydrogen fuel cell car on the market that is only 50% more expensive than a gasoline ICE car, but improves energy efficiency with 50% (first heroic assumption). Its levelized vehicle costs per kilometre would be about 40 c/km. We assume that the hydrogen is produced by steam methane reforming (SMR), an established technology used at large-scale in the petrochemical industry. With European natural gas prices at 32 c/km and if distribution costs are roughly at the same level as production costs (second heroic assumption) its levelized fuel costs per kilometre would be about 4 c/km.[3] Total costs would amount to 44 c/km of which more than 90% vehicle related and less than 10% fuel related. These basic comparative figures show clearly that even with heroic assumptions about vehicle economic conditions. Even if hydrogen would be produced and distributed free of charge, advanced hydrogen cars would still remain more expensive to drive than conventional gasoline cars.

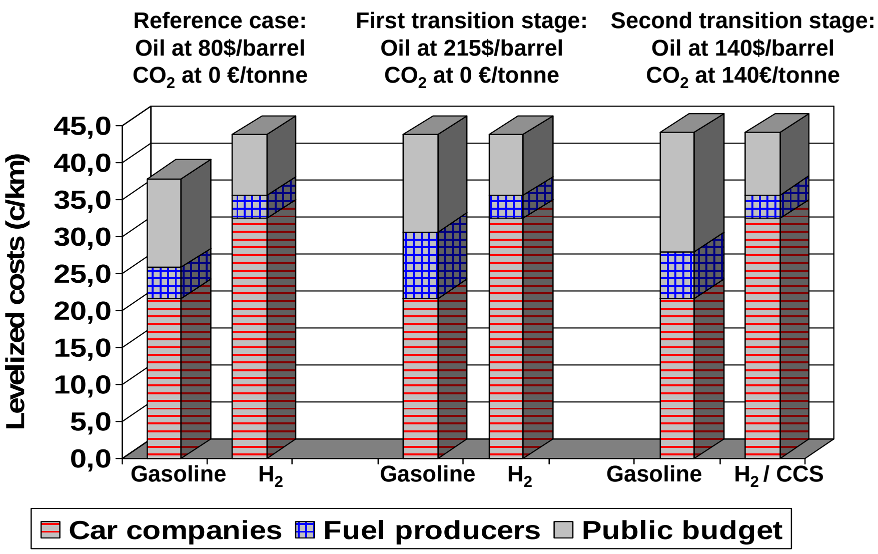



**Figure 1: Transition stages towards sustainable hydrogen economy.**

*But world oil prices may play key role in short run*

Now suppose that world oil prices increase to 215 $/barrel. This would raise the levelized costs of the gasoline ICE car to 44 c/km and there would be no need for further cost reductions along the hydrogen chain from generation to end-use (see Figure 1). An oil price of $ 215/barrel may seem extremely high, but far from implausible. It already reached close to 150 $/barrel in 2008 and the IEA presents increasingly alarming signals regarding

---

[2] Assuming vehicle efficiency of 7.5 liter/100 km, refinery efficiency of 85%, refinery cost margin of 5 c/liter, fuel distribution margin of 14 c/liter and current European fiscal regime including 65 c/liter excise tax

[3] Assuming a SMR plant efficiency of 75%, SMR production cost margin of 2 €/GJ, distribution cost margin of 12 €/GJ and current European fiscal regime including an excise tax of 2.7 €/GJ on gas for transportation purposes.

potentially dramatic developments on the global oil market in the short term [3]. However, such a high oil price would undoubtedly lead to increased investments in alternatives for conventional oil and lower liquid fuel prices in the long term.

*While $CO_2$-taxes may play key role in long run*

Similarly, one can calculate the required $CO_2$-tax to equalize levelized kilometre costs of conventional gasoline and advanced hydrogen cars. We assume here that these $CO_2$-taxes are based on well-to-wheel emissions.[4] To equalize levelized kilometer costs for both cars, $CO_2$-taxes have to reach a level of 500 €/tonne $CO_2$ for levelized costs to become equal. The plausibility of $CO_2$-taxes increasing to this level seems remote. But such high levels of $CO_2$-taxes are likely to make $CO_2$-capture and storage (CCS) in hydrogen production economically attractive and would change the underlying parameters of the calculation completely. Assuming hydrogen to be produced with SMR including CCS, a $CO_2$-tax of 140 €/tonne combined with an oil price of 140 $/barrel would make hydrogen cars competitive.[5] These figures are far from unrealistic for the period after 2020.

*However, assumption of stable fiscal regime unlikely*

Figure 1 also displays the effects on revenues for stakeholders in the automotive market from a transition from conventional gasoline to advanced hydrogen. In particular, it shows that such a transition would result in a significant reduction of government revenues, even when carbon prices become high in the long term. This may eventually lead to changes in fiscal regimes that prevent the continuous erosion of fiscal revenues. Nevertheless, this simplified static picture of competition on the automotive market demonstrates the two key messages of this analysis adequately. First, the economic feasibility of the hydrogen car can be viewed as a three-stage balancing act over time between increasing oil prices (most likely in the short term), reduced vehicle cost (most likely in the medium term) and increasing $CO_2$-taxes (most likely in the long term). Secondly, transitions to other vehicle concepts will have profound impacts on the distribution of revenues in the automotive sector, in particular on tax revenues and this is likely to lead to changing fiscal regimes along the transition path.

## 3 Competitive Position of Vehicle Options in the Long Run

*Long-term dynamics on automotive market*

The simplified picture presented as an introduction to our stylistic analysis of the battlefield for the car of the future is misleading in several ways. First of all, hydrogen fuel cell cars will not compete with conventional gasoline cars, but with new car drive trains that may use new fuels such as biofuels or electricity. Secondly, gas price developments are not independent of oil price developments and as long as hydrogen production is based on SMR processes, higher oil prices will also imply higher hydrogen costs. Finally, increasing carbon taxes will ultimately lead to new hydrogen and electricity production processes that may reduce carbon emissions drastically and thereby affect the future competitiveness of vehicle options in a

---

[4] Well-to-wheel emissions are assumed to be respectively 206 and 103 $gCO_2$/km for the gasoline ICE and hydrogen car.

[5] For this calculation we have raised the SMR production cost margin by 50% with a capture efficiency of 90%.

carbon constrained world. We will consider this dynamic storyline in the next step of our analysis.

*Basic technological data from recent IEA study*

The International Energy Agency (IEA) has recently published a detailed scenario study for global developments in the transportation sector including assumptions about performance improvements of vehicle options [4]. We have used the technological data of this IEA study as the basic data for future technological improvements for five competing vehicle concepts: the advanced gasoline ICE, the hybrid ICE, the electric plug-in, the fuel cell hybrid and the battery electric car.[6] Figure 2 illustrates the essential data presented in this study.

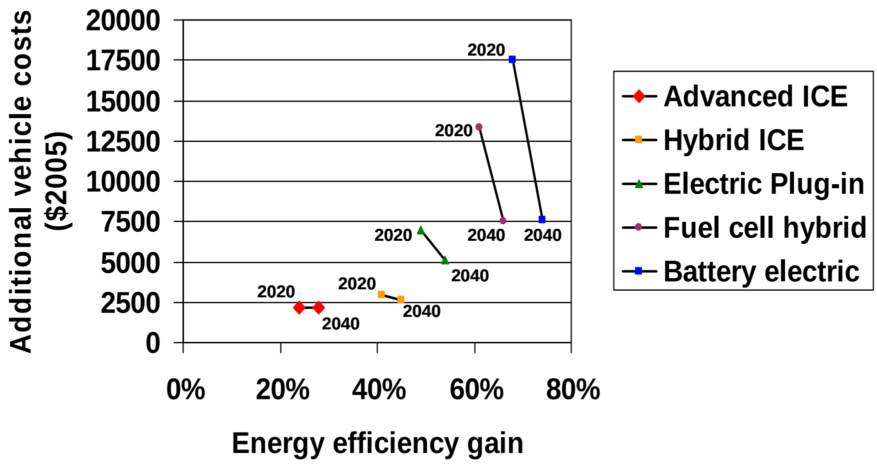



**Figure 2: Long term vehicle performance improvement.**

*Comparative performance of vehicle options in reference case*

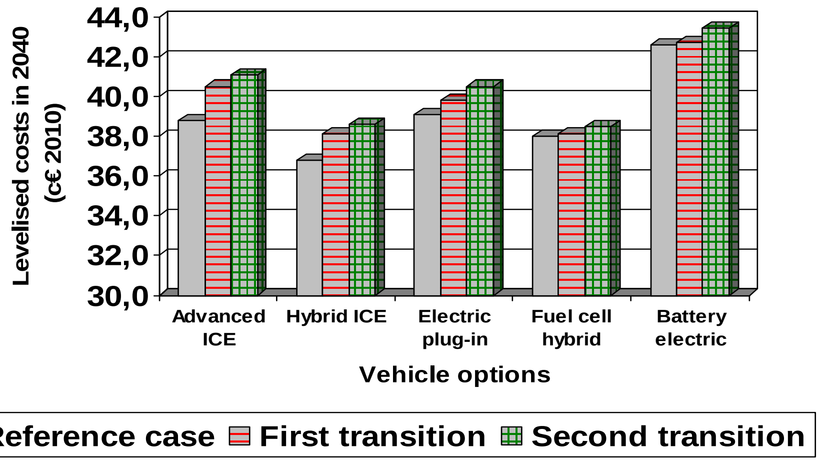
In the reference case we now follow the world oil price assumptions of the IEA transport scenarios. They assume oil prices at 100 $/barrel in 2020 and 120 $/barrel in 2030 remaining constant afterward. For European natural gas prices we assume a 2020 level of 0.36 €/m3 in 2020 and a coupling with oil prices reflecting a cross-price elasticity of 0.4.[7] European electricity gate prices are assumed to move to 0.07 €/kWh in 2020 and remain stable afterwards. For carbon prices we assume a modest level of 30 €/tonne $CO_2$ in 2020 rising to 50 € from 2030 onwards. Under these reference conditions the gasoline hybrid ICE is the

---

[6] The IEA considers 10 drive train configurations in addition to the advanced ICE vehicle. We have left out the compression ignition options here because they are essentially similar to spark ignition alternatives. We have left out the pure fuel cell alternative, because its performance will never compete with the fuel cell hybrid. From the battery electric vehicles we have only included the 200 km range vehicle. Moreover, we assume that short-term improvements are technically feasible by 2020 and long-term improvements by 2040.

[7] This relatively low estimate reflects expected changes in natural gas pricing away from conventional coupling to oil prices in long-term contracts towards independent markets with relatively ample supplies from unconventional sources.

winner in both the short and the long term (see figure 3). It is interesting to note, that the electric plug-in is the runner-up in the short term, while the fuel cell hybrid is the runner-up in the long-term. Somewhat surprisingly in view of the present electric car hype, the battery electric car is the only clear loser, both in the short term and in the long term. Apparently, many experts in transportation, both in industry and government, use different assumptions about vehicle costs and fuel prices than the IEA or they have other reasons than levelized costs calculations to sustain their views on the future of the battery electric car.




**Key assumptions: IEA performance data, first transition based on oil price of 170$/barrel, second transition based on oil price of 140$/barrel, $CO_2$ price of 140 €/tonne**

**Figure 3:** **Long-term competitive performance of alternative vehicle options.**

*First stage of transition towards sustainable hydrogen: higher oil prices*

The continued success of hybrid ICE vehicles in the short run will not only weaken the competitive position of alternative vehicle options, it will also lead to continuing pressure on global oil markets and increasing oil prices. This development will ultimately strengthen the long run competitive position of fuel cell hybrids. When oil prices would move to 170 $/barrel in 2020, the hybrid ICE would remain the winner in the short run, but the fuel cell hybrid would be able to compete in the long run.

*Second stage of transition towards sustainable hydrogen: increasing carbon taxes*

When both oil prices and carbon taxes are permanently higher than assumed in the reference case, it is not only technological change in the automotive industry that determines the competitive position of vehicle options. Technological changes in the generation of liquid fuels, electricity and hydrogen will be induced that may threaten the competitive position of the hydrogen fuel cell hybrid. In particular, biofuels will increase their share in the liquid fuel market and low-carbon electricity generation options will increase their share in the European generation mix. Also, higher levels of natural-gas derived hydrogen will undoubtedly start to affect European natural gas prices. Let us assume that an permanent oil price of 140 $/barrel would induce a 50% share of biofuels in the liquid fuel market by 2040 and that a carbon price of 140 €/tonne would induce a generation mix halving European average emissions from roughly 270 to 135 $gCO_2$/kWh by 2040. Let us also assume that under these conditions all hydrogen is produced from CCS equipped SRM plants and that natural gas prices follow oil prices completely. In this second transition stage, the fuel cell hybrid is still able to compete with the advanced ICE and continues to outperform the electric plug-in hybrid.

*The crucial role of European fiscal regimes*

The conclusions on competitive performance drawn in this analysis are based on one key assumption that may prove decisive on the battlefield between vehicle concepts: fiscal regimes in the automotive market. The calculations presented are all based on a stable fiscal regime with high excise taxes on liquid fuels, moderate excise taxes on electricity and low excise taxes on natural gas in transportation, which is representative of the average European situation today. It should be noted, that without fiscal regime changes government revenues would erode during a transition towards non-liquid, low-carbon fuels, in particular when regulatory carbon taxes prove to be effective in changing the vehicle fleet and fuel generation mix fast. Moreover, although ownership taxes offer a better window-of-opportunity to stimulate transitions towards efficient, low-carbon cars than fuel taxes in view of the limited, economic time horizon of average car owners and the increasing share of vehicle cost in total levelized costs, the European fiscal regime is moving away from vehicle ownership taxes in order to stimulate a homogenous European automotive market. If Europe wishes to compete in the oil-scarce and carbon-constrained world of the future by creating an attractive home market, innovations in long-term fiscal regime strategy are required: first replacing excise taxes with carbon taxes to absorb oil price shocks, second replacing fuel taxes with ownership taxes to stimulate entry of new vehicle concepts and finally replacing carbon taxes with road charges to prevent erosion of tax revenues in a space-constrained instead of carbon-constrained world.

## 4 What Makes a Sustainable Hydrogen Economy Feasible in the Long Run?

*Global oil price escalation, vehicle cost reduction and high carbon price levels*

Recent studies on the comparative performance of future car concepts arrive at similar conclusions regarding the future competitive position of hydrogen cars [5,6]. In this study we have analyzed specifically how oil price escalation and fiscal regimes could improve the competiveness of hydrogen cars. In our view, the economic feasibility of the hydrogen car and thereby the hydrogen economy can be viewed as a three-stage balancing act between increasing oil prices (most likely in the short term), reduced vehicle cost (most likely in the medium term) and increasing $CO_2$-taxes (most likely in the long term). This is the first major message of this analysis. A sustainable hydrogen economy depends on consecutive, major changes in these three key economic parameters. Global oil price escalation must first reduce the competitive edge of the fossil fuel hybrid ICE around 2020. Than hydrogen vehicle cost must be reduced drastically after 2020 to gain share in the market and finally, increasing carbon taxes must induce a continuous shift towards low-carbon generation technologies that could dominate the fuel market after 2030 and favour hydrogen cars.

*Sustainable fiscal regime strategy must interact flexibly with market forces*

Policy makers can actively strive to guide the evolving automotive market in a sustainable direction by consecutive changes in fiscal policies that support the move towards low-carbon vehicle choices. The present European fiscal regime is inclined towards high levels of excise taxes on liquid fuels and zero vehicle ownership taxes that are considered detrimental for a competitive European market. The feasibility of a sustainable hydrogen economy would be substantially enhanced, if European fiscal regimes would follow a flexible strategy, in which today's excise taxes on liquid fuels are gradually replaced by increasing carbon taxes that keep government revenues stable in the short run. Once vehicle costs enter competitive levels, ownership taxes and subsidies (bonus-malus arrangements) should speed up penetration rates. But ultimately, regulatory carbon taxes, if successful in reducing emissions drastically, would again erode the tax base. At that time, road charges may have gained sufficient support to follow-up fuel charges and keep governments revenues stable.

**References**

[1] HyWays – The European Hydrogen Roadmap, European Community, Brussels, 2008

[2] Transitions to Alternative Transportation Technologies – A Focus on Hydrogen, National Research Council of the National Academies, Washington, 2008

[3] World Energy Outlook 2009, International Energy Agency, Paris, 2009

[4] Transport, Energy and CO2 – Moving towards Sustainability, International Energy Agency, Paris, 2009

[5] Vliet, Oscar P.R., Thomas Kruithof, Wim C. Turkenburg and André Faaij, Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars, *Journal of Power Sources*, vol. 195, 2010, pp. 6570-6585

[6] Offer, G.J., D. Howey, M. Contestabile, R. Clague, N.P. Brandon, Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system, *Energy Policy*, vol. 38, 2010, pp. 24-29

# User Perceptions and Public Attitudes towards Hydrogen Fuel Cell Fleet Vehicles in the EU

**Katja Pietzner**[*], **Natalia Morgunova**, **Maria Yetano**, **Peter Viebahn**, Wuppertal Institute for Climate, Environment, Energy, Germany

## 1 Description of Hychain Project

The HYCHAIN MINI-TRANS project is an Integrated Project funded through the 6th Framework Programme of the European Union. It is one of the leading hydrogen demonstration projects of the European Commission's Transportation and Energy Division and is the first project of this nature to be implemented. The project with a network of 24 European partners runs from January 2006 to June 2011 under the co-ordination of Air Liquide.

HYCHAIN MINI-TRANS allows citizens from four European Community regions to test a group of 46 small urban vehicles including small utility vehicles and midi-buses, wheelchairs and cargo-bikes, all powered by hydrogen fuel cells. This project also demonstrates the use of innovative logistics for hydrogen distribution. The four partner regions are: Rhône-Alpes in France (Grenoble Alpes Métropole Agglomeration Community), Castilla y León region in Spain (city of Soria), North Rhine Westphalia in Germany (region of Emscher-Lippe) and the city of Modena in Italy. Public and private fleets are currently operating the vehicles in every-day use: municipal services, public transport, last-mile logistics and personal transport by people with disabilities.

The following four-step approach has already been implemented: (1) the project started from existing prototypes of five low-power fuel cell applications that were optimised in design and functionality, (2) pre-commercial manufacturing lines were set up to reduce costs as well as to improve quality, (3) the required hydrogen distribution logistics and services (transport, distribution, dispensing) were established based based on an innovative refillable storage solution and (4), a network of comparable subprojects using the common demonstration vehicles is being implemented in the four participating regions.

As with the introduction of any new technology, there are a number of social acceptance issues in the field of hydrogen and fuel cell technologies which have to be investigated. The HYCHAIN project is one of the main projects currently underway for the demonstration of hydrogen and fuel cell technologies in Europe. With its focus on low-power urban transport applications, HYCHAIN provides an optimal test-bed for the assessment of the reactions of a wide range of stakeholders to the new technology. A number of these stakeholders will be in touch with the HYCHAIN vehicles relatively directly (regional authorities, fleet managers, drivers, technicians and users/passengers) and can hence provide first-hand signs of the attitudes that are likely to develop in these various groups once greater penetration of the technology takes place. The attitudes of the greater population who have not yet used the

[*] Corresponding author, email: katja.pietzner@wupperinst.org

technology can also be studied within the project and compared to those of the population which is directly in touch with the technologies.

## 2 Wuppertal Institute's Tasks

Within the international consortium of 24 partners, under the overall coordination of Air Liquide S.A., the Wuppertal Institute for Climate, Environment and Energy acts as the responsible coordinator for work package 8 "Innovation Activities" that comprises the following tasks:

- Dissemination activities distinguished between European and national/regional activities.
- Techno-economic and environmental assessment of technologies.
- Socio-economic studies, providing the necessary insights on how to maintain and to enlarge the use of hydrogen applications in early markets.
- Exploitation of results: the outcome of the socio-economic study package will be used to develop strategies for further exploitation of HYCHAIN-MINITRANS technologies, both on national and international levels.

## 3 Socio-Economic Studies

The first step of the socio-economic studies is the development of evaluation tools suitable for the study's needs: self-completion questionnaires, face-to-face interviews, online polls and other methods will be used.

The surveys are directed to different target groups due to different aspects of perception concerning the HYCHAIN-project: drivers, passengers, vehicle minders, operators, service-centre-staff and the local public, to mention some of them.

The HYCHAIN socio-economic studies will aim to answer the following lead questions:

- What is the level of satisfaction and what are the perceptions of users (drivers, maintenance personnel, fleet managers, passengers) in terms of HYCHAIN vehicle performance in daily operation and towards hydrogen as an energy carrier in general?
- What are the perceptions, attitudes and preferences of potential user groups (in the participating regions) with regards to the HYCHAIN vehicle concepts and towards hydrogen as an energy carrier in general?
- How did perceptions and attitudes change under a framework of increased information about the technology (influence of knowledge and experience)?
- What is the value of the non-market benefits (e.g. decreased local pollution) brought about by the vehicles, as elicited from environmental valuation surveys in the public?

## 4 First Research Insights: Survey on Midibus Drivers in Germany

The first inquiries started in autumn 2009 with the drivers of the two midibuses deployed in the Emscher- Lippe region (Germany).

The questionnaire contained 27 questions regarding personal experiences, satisfaction with the bus, safety and maintenance aspects of the vehicle, the training courses, attitudes and knowledge and finally sociodemographic data. The sample consisted of 32 male drivers with an average age of 45.3 and a solid experience as a bus driver of more than 10 years for 96.9% of all respondents. At the time the survey was conducted most of the drivers drove the vehicle on a regular basis of several times a week (42%) or several times a month (36%). As an example of the results, Figure 1 shows the drivers' satisfaction with the Midibuses' overall performance. 44% of the drivers are satisfied with the vehicle's overall performance (14 drivers), yet 22% of the interviewees declare themselves to be rather unsatisfied (7 drivers), while one third were undecided (10 drivers). Due to the fact that the buses were operated in regular service from the beginning, these results conform to prior expectations of mixed reactions to the new technology.

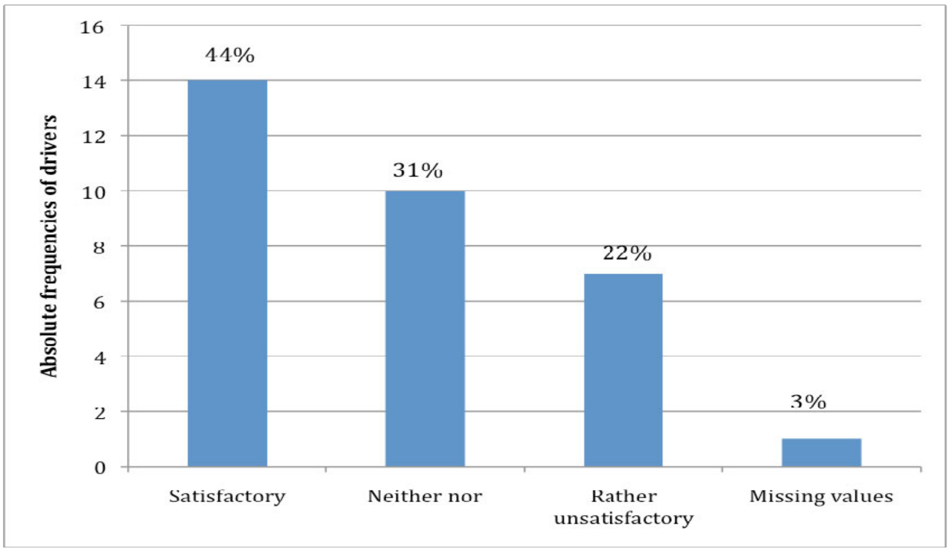



**Figure 1: Frequencies of drivers' satisfaction with the Midibus overall performance (n=32).**

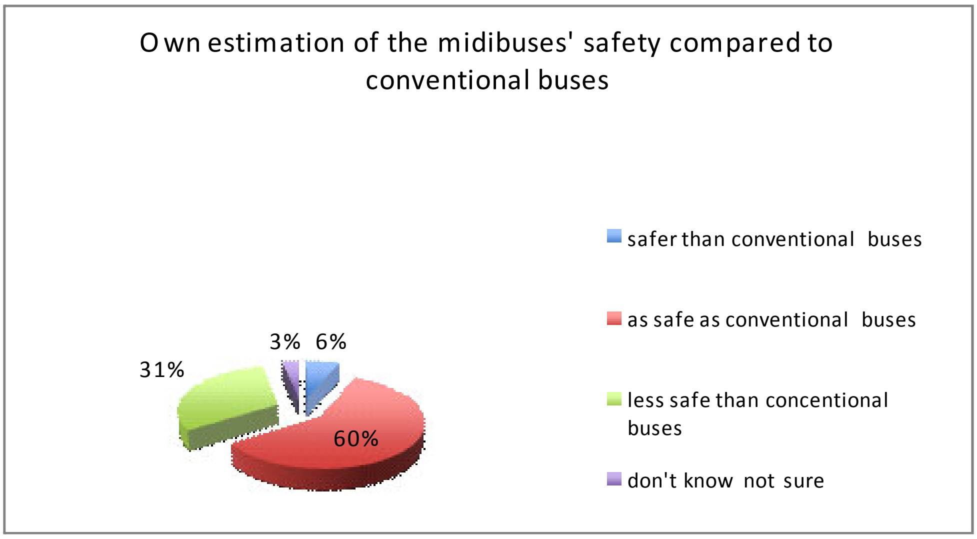



**Figure 2: Frequencies of drivers' interest regarding Midibuses' safety (n=32).**

The aspects named the most to be unsatisfactory were “speed” and “driving noises”. The drivers mostly describe their own interest in hydrogen as very or rather strong whereas only 6% are indifferent concerning this topic. The bus safety is estimated to be the same compared to conventional buses (60%), whereas 31% state that the midibus is less safe than a conventional bus.

## 5 Next Research Steps

The evaluation of the HYCHAIN projects consists of several investigative steps, which are on schedule for the year 2010. The next research steps include the follow-up survey on perceptions and attitudes of midibus drivers, as well as the survey of other vehicle drivers and target groups. Each driver group will be interviewed twice in order to gather the evolution in their opinions over time. Drivers will continue to be surveyed through self-completion-questionnaires, whereas face-to-face interviews are planned for other groups of interest e.g. service-centre-staff, infrastructure-operators, decision makers and fleet managers. The surveys regarding the project’s acceptance in the local public will be organized with the help of web applications, which allow a simple and quick programming of a questionnaire and an automatic response collection. The recruitment of a representative sample will be carried out by a professional online polling company. Finally a workshop for multipliers and stakeholders is planned. Representatives of influential groups concerning the project will be asked to participate in a panel discussion in each region. Such representatives would for example be government officials, journalists or regional stakeholder and researcher scientists. The following table presents some insights of the next research steps within the user perceptions and public acceptance surveys.

**Table 1: Time schedule for the next research steps to conduct the perceptions and acceptance regarding HYCHAIN vehicles.**

| HYCHAIN communities in France, Germany, Italy and Spain | | HYCHAIN fleet<br>Time schedule for the next research steps | | | |
|---|---|---|---|---|---|
| Evaluation type | | Midibus | Cargobike | Utility Vehicle | Weelchair |
| Questionnaires | Drivers | Two survey waves in April and September 2010 | | | |
| | Passengers | Survey planned from May to July | | | |
| | Local Public | Survey planned from May to July | | | |
| | Minders | Survey planned from May to July | | | |
| In-depth interviews | Infrastructure Operator | Survey planned from September to December | | | |
| | Service Center Stuff | Survey planned from September to December | | | |
| | Fleet manager | Survey planned from September to December | | | |
| | Decision makers | Survey planned from September to December | | | |
| Workshops (optional) | Multipliers & Stakeholders | Survey planned from September to December | | | |

## 6 Outlook

The first survey results with Midibus drivers in North-Rhine-Westphalia revealed a quite positive perception regarding the hydrogen fuel cell vehicles. The conference presentation will give more detailed insights and show whether these results were confirmed by the data from all four countries.

In summary, the surveys provide a comprehensive knowledge base on the perceptions and acceptance of hydrogen fuel cell vehicles in the four selected European communities. Our results will shed light into the local understanding and knowledge of hydrogen related issues, and possibly reveal existing misconceptions concerning hydrogen and fuel cell vehicles. The embedded in-depth interviews will provide insights in how security aspects affects hydrogen evaluations. These results will be evaluated and discussed with regard to their implications for hydrogen and fuel cell communication and implementation methods.

# How to Improve the Public Perception of Hydrogen?

**Chakib Bouallou**, **Joao de Castro**, MINES ParisTech, Centre Energétique et Procédés, France
**François Werkoff**, Association Française de l'Hydrogène, France

## 1 Introduction

Most of countries which promote research and development programs on hydrogen energy have considered the public acceptance. In the open literature, results of some opinion polls are available, which have been performed in USA, Canada, Japan, Germany, Island….

In order to provide a first basis to the AIDHY project, (the objective of which is to improve the public acceptance of hydrogen as an energy vector and is supported by the French *Agence Nationale de la Recherche*), the AFH2 (*Association Française de l'Hydrogène*) has realized two opinion polls, during year 2008. The first one, during the fair of Transports and sustainable mobility, during September, in the gardens of Trocadéro and the second, on the occasion of the exhibition for equipment, technologies and services of environment (Pollutec), in Lyon, during December. We will provide the notable results of these two polls.

We will present a synthesis of opinion polls in various countries and briefly point out, the initiating circumstances, methodologies, classes of public…

Finally, we will examine how the information given to several categories of people, can influence the perception of problems linked to hydrogen energy and provide a few recommendations in order to improve the public acceptance of hydrogen.

## 2 Notable Points of the Two Opinion Polls Realized by the AFH2, during Exhibitions [1]

- The number of persons thinking that the electrolysis of water is today, the main process for producing hydrogen is lightly greater than that of persons thinking that it is the reforming of fossil materials.
- The use, by the past of hydrogen is ignored of the public. In practice nobody knows the two main components of the ancient city gas: hydrogen and monoxide of carbon.
- The massive production of hydrogen by electrolysis from electricity produced without $CO_2$ emission is predominantly considered possible for 2040, and satisfactory for most the persons having this point of view.
- The use of hydrogen in transport should be the most developing in 2040, followed by the storage of the energy either for intermittent renewable energy sources, or in the regulation of the peaks of production of electricity.
- Most of the people think, that in France, the information on technologies of hydrogen is not sufficient.

## 3 Synthesis of Opinion Polls in Various Countries

A classification of opinion polls which have been realized in various countries is reported in Table 1. It is possible to distinguish two main categories. Sometimes, questionnaires have been submitted to people at the occurrence of demonstration programs in relation with the use of hydrogen energy (generally hydrogen buses), in the following, there will be called post-introduction polls. At the opposite ,in some other cases, questionnaires have been proposed independently of demonstration programs, i.e. to people that never were confronted to hydrogen vehicles, for this reason, we will make mention of pre-introduction opinion polls.

Pre-introduction polls were performed in Germany, U.S.A. and France. The public acceptances for these three countries are reported in Figure 1.

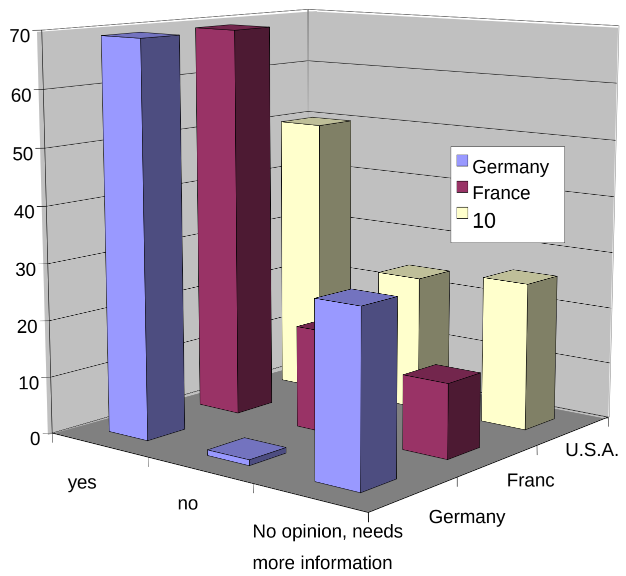



**Figure 1: Public acceptance for pre-introduction polls.**

We can see that approval is rather good. However many people wish to have more information. Acceptability is better in a country which is leader in hydrogen (Germany), than in a country which follows tendency (France).

As an illustration on how the public acceptance is influenced by the demonstration programs, we present in Figure 2, opinions in favour of the introduction of the fuel cells, for all the pre and post-introduction polls, which are mentioned in Table 1.

As a rule, opinions are favourable, as well in pre-introduction as in post-introduction. The proportion of favourable opinions is increased by demonstration programs, mainly when people can use buses instead of seeing them only. The number of persons without opinion is also much less important in post-introduction than in pre-introduction. In both categories the lack of information and knowledge is a recurrent problem.

**Table 1: Classification of opinion polls.**

| | Post or pre-introduction | Number of polled persons | Shares Men / Women | Employment | Mean for collecting opinions |
|---|---|---|---|---|---|
| Germany* [2] | Pre | 345 | | | By telephone |
| | Post | 200 | 50/50 | | Inside a bus |
| Canada [3] | Post | 369 | 37/45 (18% did not answer) | Student: 31% Retired: 5% Other: 64% | Inside a bus |
| France [1] | Pre | 106 | | Student: 11% Retired: 15% Other: 74% | During exhibitions |
| Island [4] | Post | 200 | 50/50 | | Inside a bus |
| Japan [5] [6] | Post | 489 | | | On the street |
| | Post | 400 | 50/50 | | On the street |
| U.S.A. [7] | Pre | 889 | 48/52 | | By telephone |

**For the AcceptH2 Project, piloted by Germany, opinions have been collected, not only in Berlin, but also in London and Perth.*

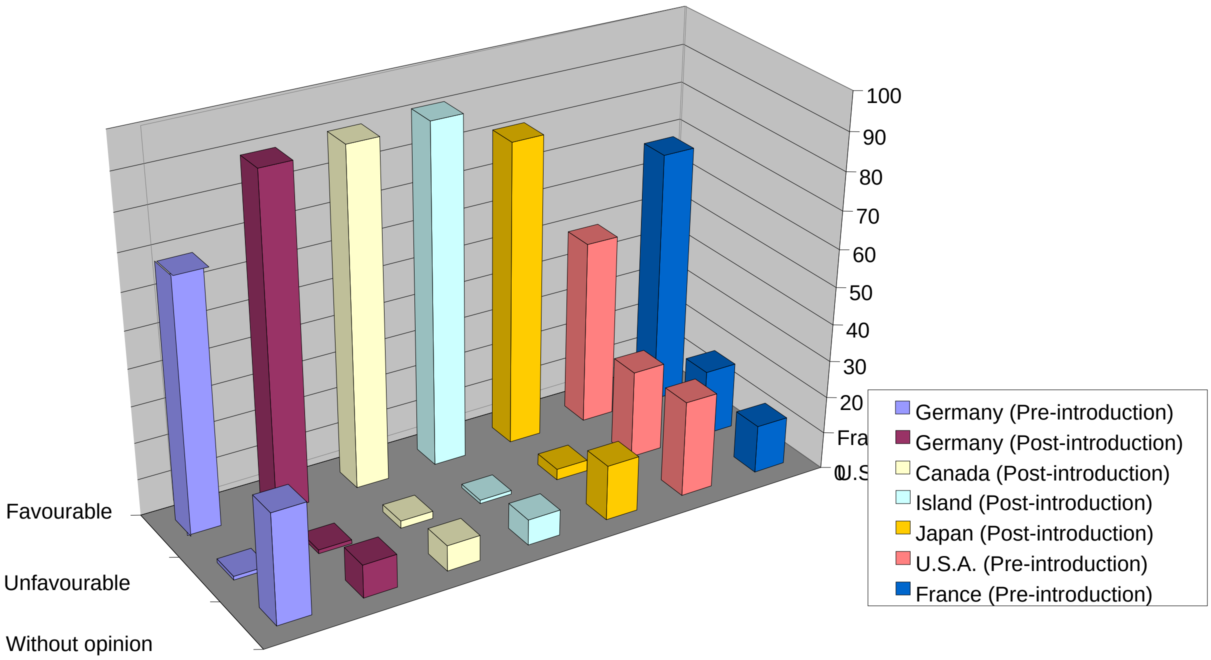



**Figure 2: Opinions related to the introduction of the fuel cells.**

## 4 Conclusion

At the occurrence of opinion polls, various questionnaires were proposed to several categories of people. It appeared that the acceptance of people is better when hydrogen as a fuel has been in public discourses. Among the favourable aspects, the ecological advantage is often advanced. The fact that at present, the hydrogen is mainly produced by reforming of the fossil resources is greatly ignored. The risk of explosion is an argument against the hydrogen, but almost nobody remembers that the hydrogen was distributed in cities during more than a century as a major component of the synthesis gas, produced from the coal and used for the lighting and the cooking of food. It is not known that until very recently the main use of the hydrogen was for the manufacturing of fertilizer and that it is now exceeded by the needs of the petroleum refineries which increase very quickly. In conclusion, we recommend not limiting the information about the hydrogen to the end uses of bus and cars working with fuel cells, but to extend it to the past and present uses of hydrogen, as well as to the other aspects of the chains from production to end uses, with a particular care for the ecological processes of production of hydrogen, without greenhouse gas emission.

### References

[1] AFH2: http://www.afh2.org/f/index.php?c=&p=&index=3

[2] M. Altmann et al. Public Acceptance and Economic Preferences Related to Hydrogen Transport Technologies in Five Countries,.15th WHEC, Yokohama, Japan, June 27- July 2, 2004.

[3] And: http://www.accepth2.com/results/docs/AcceptH2_D9_Full-Analysis-Report_050804.pdf

[4] A Hickson, Al. Phillips and G. Morales. Public perception related to a hydrogen hybrid internal combustion engine transit bus demonstration and hydrogen. Energy Policy, April 2007, Vol.35, Issue 4, Pp. 2249-2255

[5] M.H. Maack and J.B. Skulason. Implementing the hydrogen energy. Journal of Cleaner Production, 2006, Vol.14, Pp. 52-64.

[6] Y. Matsumoto, H. Uemura, T. Kai, Study on public acceptance of hydrogen energy. Case study in Yakushima. Proceedings of the 5th Asian Pacific Conference on sustainable energy and environmental Technology, 2005.

[7] H. Akamatsu. Report on Public Relations Activities, 2004. http://jhfc.jp/e/data/seminar/fy2004/pdf/7_2004.pdf

[8] R. Schmoyer and T. Truett: Hydrogen Knowledge and Opinions Assessment. 2008. http://www.hydrogen.energy.gov/pdfs/progress08/ix_1_schmoyer.pdf

# Fuel Cell and Hydrogen ($FCH_2$) Technology Creates Business Opportunities beyond Products and Applications

**Marcel Corneille**, EMCEL Engineering, Germany
**Alexandra Huss**, AKOMBE Technology and Market Communications, Germany

## 1 $FCH_2$ and Climate Policy

The evolution of advanced energy technologies over the last years is a result of the increasing focus on the significance of climate issues. Hydrogen and fuel cell technologies have been part of this evolution. Where the topics of energy demand, energy safety, greenhouse gas emissions and economic development are concerned, there is no longer any doubt that electricity and hydrogen will become the energy carriers of the future involving new and highly efficient energy converters such as fuel cells.

The German Government and the European Union directed their environmental and energy programs in directions that will continue to support the introduction of renewable energies and advanced technologies. Together with industry and the research community, funding programs have been created and gradually implemented. According to the German Federal Ministry of Transport, these activities are essential to prepare for the fuel cell and hydrogen markets of the future. As with all innovations and emerging technologies, fuel cell and hydrogen technologies will create value for companies and organisations in all types of business. The result will be the generation of new fields of work and new jobs.

## 2 $FCH_2$ and Job Creation

Although there are still only a limited number of fuel cell products on the market, the technology and its specific requirements demand know-how and skills in various fields along the value chain. Fuel cell technologies across all industries involved have matured since the early years of research and development. Funding programs for the market introduction of products and applications are intended to create the momentum necessary to accelerate widespread commercialisation. As part of this process, companies will ramp up their internal capacities which will lead to the creation of new jobs. Most of the current jobs and positions are in the field of research and development activities for products and applications.

In the near future, jobs will also be created in other business fields. According to a study of Fuel Cell Today published at the end of 2009, the fuel cell industry could create 700,000 manufacturing jobs worldwide over the next decade. Looking at projections of unit shipments over this period, over a million new jobs could be created in the areas of fuel cell installation, servicing and maintenance.

According to statistics of the German Engineering Federation (VDMA), the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) and the National Organisation for Hydrogen and Fuel Cell Technology (NOW), there are about 400 to 500 companies in Germany alone dealing in some way with $FCH_2$ technology of which 100-200 belong to the supplier industry. From 2010 onwards a strong growth in new jobs is anticipated.

In Germany, fuel cell and hydrogen technologies are considered part of the renewable energy sector. If Germany is in fact able to realise its climate objectives, an annual 2.5% growth and a creation of 630,000 additional jobs can be expected in this field by 2020[1]. According to the German Federal Environment Agency (UBA), climate issues (or environmental protection) will be the driver for innovation in this century.

## 3 FCH₂ and the Service Sector

The growing fuel cell and hydrogen sector is creating new business opportunities for specialists and experts, particularly in the service sector. Services include engineering, consulting and marketing services, services in the field of (further) education and training, and maintenance services for $FCH_2$ products.

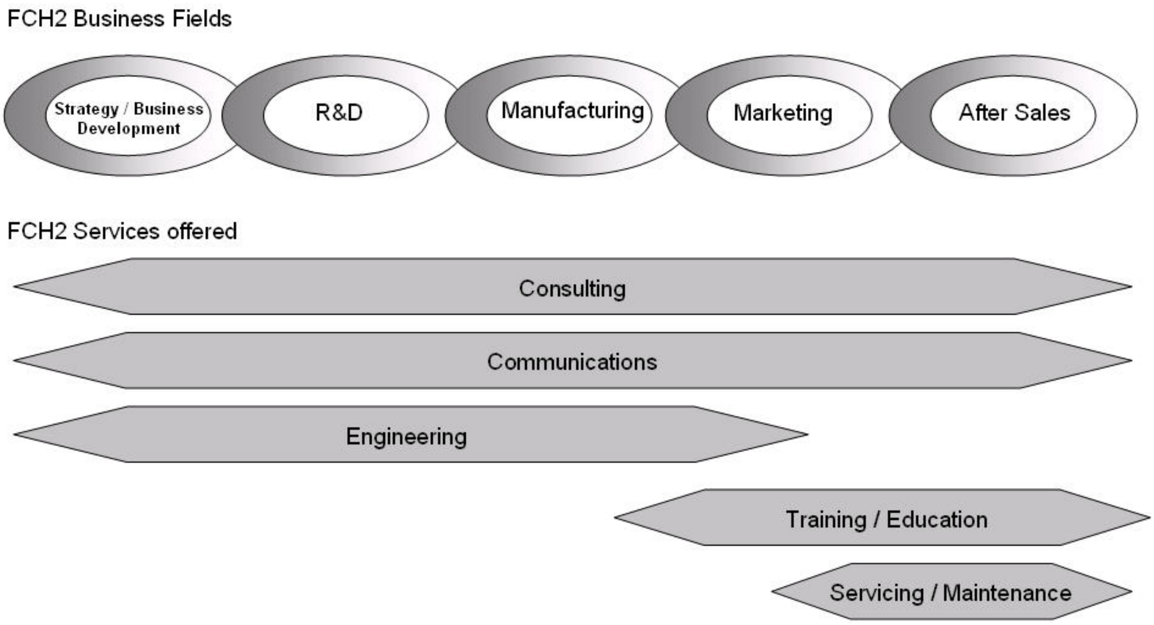



**Figure: $FCH_2$ Business fields and services offered.**

- **Engineering** companies provide services such as simulation, software development, and design, as well as mechanical, process and production engineering and project management for all stages of the $FCH_2$ research and development process.
- Regarding **consulting** services for $FCH_2$, the focus lies on strategic business development for small and medium-sized companies as well as for governmental institutions whose goal is the economic development of their respective regions.
- **Communication** services support the market introduction of $FCH_2$ technologies. These services ensure that information about $FCH_2$ technology and applications are communicated successfully to the stakeholders and target groups in the right context (when, where and how).

---

[1] See interview Süddeutsche Zeitung, 20.02.2010 with Jochen Flasbarth, President of the Federal Environment Agency, Germany

- Services in the field of **training and (further) education** are essential to familiarize affected professional groups with the changes in their fields of work, as well as to help schools and universities create new courses of study and adapt existing ones to meet the requirements of the $FCH_2$ industry.
- Finally, services are offered in the field of **servicing and maintenance** for existing $FCH_2$ products, owing to the limited number of educated and trained craftsmen, technicians, mechanics or electricians and because it is still too expensive for smaller organisations to invest in their own personnel.

## 4 $FCH_2$ and Expert Services

Conventional services as we find them in conventional industries will not be sufficient when it comes to fuel cell products and hydrogen energy. Although the services being provided for $FCH_2$ technology do not appear different on the surface, one will find that the individuals behind them have a keen insight into this new and evolving business and have – in the meantime - set up their own businesses after working many years in the $FCH_2$ industry. They are most knowledgeable about the industry and have exceptional expertise about $FCH_2$ technology having acquired their work experience in companies which belong to the pioneers of the $FCH_2$ industry in their respective countries. These experts are familiar with the industry's risks and its opportunities, because they have been involved in its evolution.

Already today experienced engineers, qualified managers and competent marketing experts are offering their know-how in services for all kinds of $FCH_2$ fields of business. They support all sizes of companies and institutions flexibly and for as long as necessary. This gives the companies and institutions employing these individuals the organizational freedom needed in a young and emerging $FCH_2$ business environment.

### Example 1: EMCEL Engineering – A $FCH_2$ Engineering and Consulting Company

The areas of expertise of EMCEL Engineering are alternative drive trains and fuel cell and hydrogen technologies. The company's head is a mechanical engineer who worked for more than a decade in the research & development sector for automotive fuel cell applications before he started his own business. With the information and know-how gained in the $FCH_2$ industry, EMCEL Engineering now supports small and medium-sized companies who have discovered the $FCH_2$ industry as a potentially new market for their products. EMCEL Engineering also supports established fuel cell players in times when the work load is high and when special know-how and knowledge about specific markets is needed.

### Example 2: AKOMBE – Technology & Market Communications

AKOMBE's area of expertise is in the field of advanced energy and powertrain systems including hybrid, battery and fuel cell technology, advanced ICE concepts as well as renewable energies. The owner has a business degree and worked for years in the field of marketing communication for automotive $FCH_2$ applications. During that time, she worked closely with developers, researchers and managers and acquired extensive technical know-how. She is familiar with the technical benefits and problems, understands the technology in detail, and is in a position to assess the statements of experts. This makes her a competent consulting and business partner.

# Lessons for Low-Power Fuel Cell Vehicles from a Demonstration Project: Results of Techno-Economic, Safety, Environmental and Social Assessment of the EU-HYCHAIN MINI-TRANS Project

**Peter Viebahn**[*], **Katja Pietzner**, Wuppertal Institute for Climate, Environment, Energy, Germany
**Antoni Laurent**, CEA, France
**Yolanda Lechon**, CIEMAT, Spain

## 1 The Hychain Project

The HYCHAIN MINI-TRANS project is an Integrated Project funded through the 6th Framework Programme of the European Union. It is one of the leading hydrogen demonstration projects of the European Commission's Transportation and Energy Division and is the first demonstration project of this nature to be implemented. The project, with a network of 24 European partners, runs from January 2006 to July 2011 under the co-ordination of Air Liquide.

The HYCHAIN MINI-TRANS Project allows citizens from four European Community regions to test a group of 53 small urban vehicles including small utility vehicles and midi-buses, wheelchairs, scooters and cargo-bikes, all powered by hydrogen fuel cells. This project also demonstrates the use of innovative logistics for hydrogen distribution. The four partner regions are: Rhône-Alpes in France (Grenoble Alpes Métropole Agglomeration Community), Castilla y León region in Spain (city of Soria), North Rhine Westphalia in Germany (region of Emscher-Lippe) and the city of Modena in Italy. Public and private fleets are currently operating the vehicles in every-day use: municipal services, public transport, last-mile logistics and personal transport by people with disabilities.

The following four-step approach has already been implemented: (1) the project started from existing prototypes of five low-power fuel cell applications that were optimised in design and functionality, (2) pre-commercial manufacturing lines were set up to reduce costs as well as to improve quality, (3) the required hydrogen distribution logistics and services (transport, distribution, dispensing) were established based on an even exchange of innovative refillable storage solution and (4), a network of comparable subprojects using the common demonstration vehicles are being implemented in the four participating regions.

Technical deployment is complemented by socio-economic research targeted at overcoming the main current barriers, such as stakeholder awareness and public acceptance, certification, training, etc. Dissemination and exploitation activities provide the framework for maintaining the momentum and triggering a sustainable market growth in several lines of applications.

---

[*] Corresponding author, email: peter.viebahn@wupperinst.org

## 2 Technology Assessment as Part of Innovation Activities

HYCHAIN assesses the results of the project in five different dimensions:

- *technical* (e.g. component performance, maintenance needs)
- *economic* (life-cycle costs of vehicles and of hydrogen logistics)
- *safety* issues
- *environmental* (well-to-wheel analysis and environmental impact analysis) and
- *social* (user perceptions and public acceptance of the technology).

The assessment is mostly based on data collected through an on-line system that centralises the data resulting from daily operation of the vehicles and associated hydrogen infrastructure. Based on this assessment, a forecast of HYCHAIN MINI-TRANS evolution, as well as innovation and policy-oriented conclusions will be carried out at the end of the project.

The presented poster gives insights into the first results of the five assessment dimensions, focusing mainly on the technological, environmental and user perception assessment. The following sections present some first results. At the time of poster presentation, further data on the deployment of most vehicles will be included into the assessment.

## 3 Status of Deployment Phase

The deployment phase of the HYCHAIN MINI-TRANS vehicles started in May 2009 when the first two midi-buses were delivered to the public transport company Vestische in the Emscher-Lippe region. Till the deadline of this abstract, 21 vehicles have been deployed (3 midi-buses, 6 cargo-bikes, 7 wheelchairs and 5 utility vehicles, see Figure 1). All other planned vehicles have been manufactured and are awaiting distribution from May 2010.

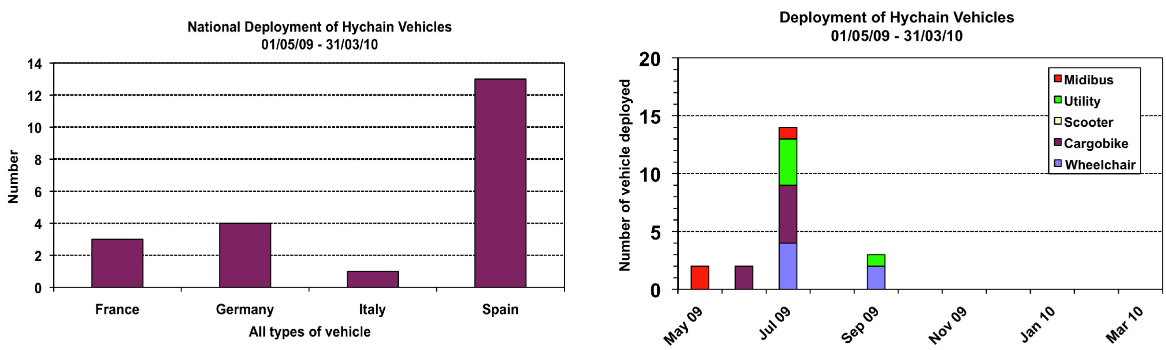
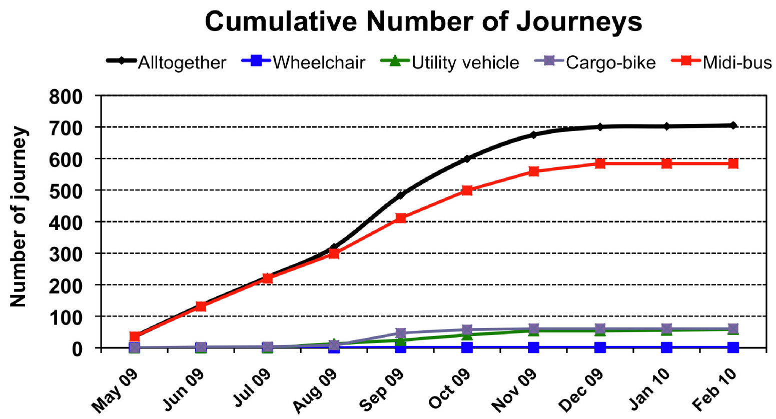



**Figure 1: Deployment of HYCHAIN MINI-TRANS vehicles (by country and by type).**

## 4 First Results of Technological Performance Monitoring

Figure 2 illustrates cumulative figures for the number of journeys and driven distance over all vehicles. As can be seen, most journeys done so far were journeys of the midi-buses (584 journeys = 83% of total). Furthermore, midi-buses dominate the distances travelled by 94% (21,900 from 23,350 km in total). The remaining distance was driven by utility vehicles (1,200 km in 60 journeys) followed by cargo-bikes (252 km in 60 journeys). Although all wheelchairs are deployed, no journeys have been made, due to user selection problems.

None of the vehicles have been running since December. In the case of the midi-buses, this is due to technical problems which are unrelated to the hydrogen and fuel cell components. All other vehicles are not able to be used at temperatures below of 5° Celsius which means they had to stop their operation. When presenting the final poster, updated figures up to April 2010 will be shown.



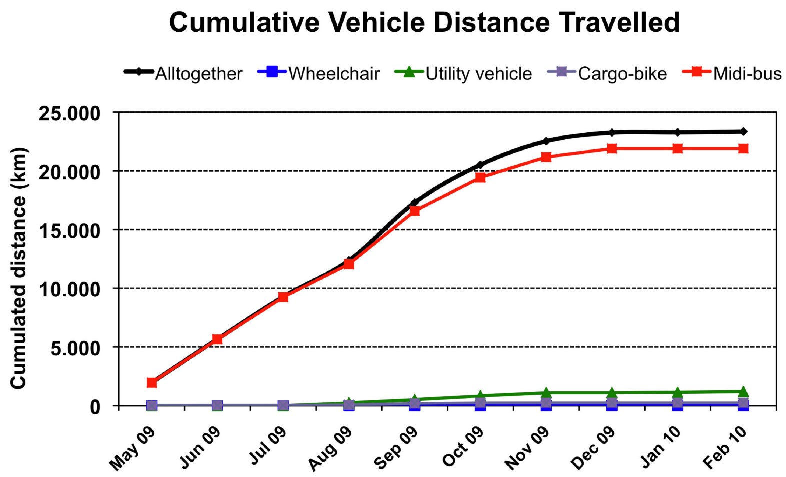




**Figure 2: Cumulative number of journeys and distance travelled since start of deployment.**

Figure 3 gives a more detailed view on the three midi-buses in operation. Two of them are used for public transport in the Emscher-Lippe region (7 days a week), one in the Spanish city Soria (5 days a week). The buses show a real success story of HYCHAIN MINI-TRANS (11,200 and 10,020 km driven by the buses in Germany; 820 km in Spain). They have a technical availability of 72 – 75%, which is more than initially expected. The target for the next months is to achieve a higher range since the German operating company wants to enhance the buslines to cover a larger area in their region. Currently a range of 130 – 138 km can be achieved, while the theroetical range, calculated for standard conditions, is 176 km.

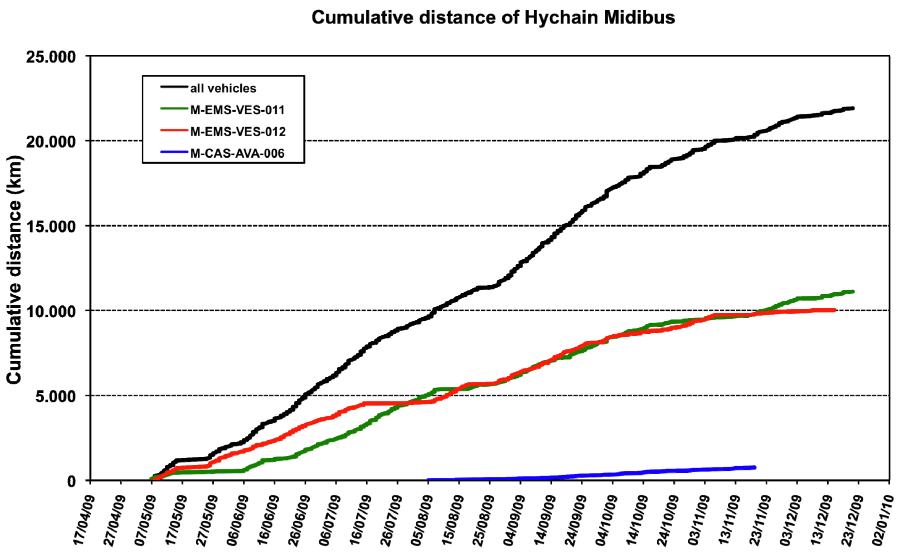



**Figure 3: Distance travelled by the midi-buses in operation in Germany ("EMS") and Spain ("CAS").**

Finally, Figure 4 illustrates the effect of the operation in different conditions. The cargobikes are used in the centre of the cities or at the premises of companies with distances ranging between one and five kilometres. The minibuses have a higher range between 10 and 90 kilometres. Whereas the German buses are operating in the countryside driving distances between 50 and 80 km per journey, the Spanish bus is operated within the city of Soria covering distances between 5 and 25 km per journey on average.

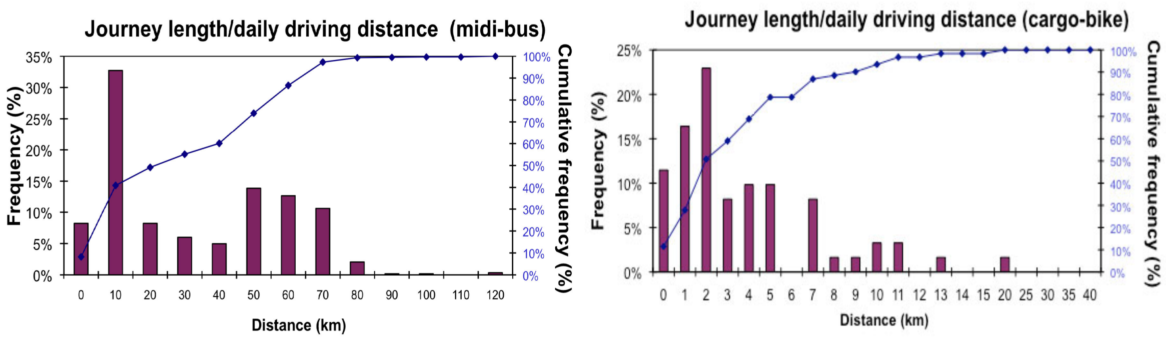



**Figure 4: Journey length and daily driving distances of cargo-bike (left) and midi-bus (right).**

## 5 First Results of the Well-to-Wheel and Environmental Impact Analysis

The environmental assessments performed in HYCHAIN MINI-TRANS are divided into a Well-to-Wheel (WtW) assessment of the hydrogen production plus an Explorative Environmental Impact Assessment (EEIA) of those parts of the vehicle that markedly differ from the reference vehicles.

The *WtW analysis* assesses the energy consumed from hydrogen production to its use in the fuel cell vehicle – and corresponding $CO_2$ emissions – in order to get information about the energy use and environmental impacts of hydrogen production and use within HYCHAIN technologies. This data is compared to the corresponding reference technology (ICE vehicles and electric vehicles). The process chain can be segmented as:

- *Well-to-gate*: actual industrial $H_2$ supply by Air Liquide
- *Gate-to-tank*: HYCHAIN hydrogen logistics and distribution by vehicle
- *Tank-to-wheel*: specific operation figures of the vehicles

As Figure 5 shows, the greenhouse gases (GHG) emissions evaluated for a HYCHAIN midi-bus are an estimated 345 g eq. $CO_2$/km, considering a 200 km range. The GHG emissions calculated for the reference midi-bus (electric vehicle) are rather similar (348.5 g eq. $CO_2$/km), considering a European electricity mix and a 100 km effective battery range.

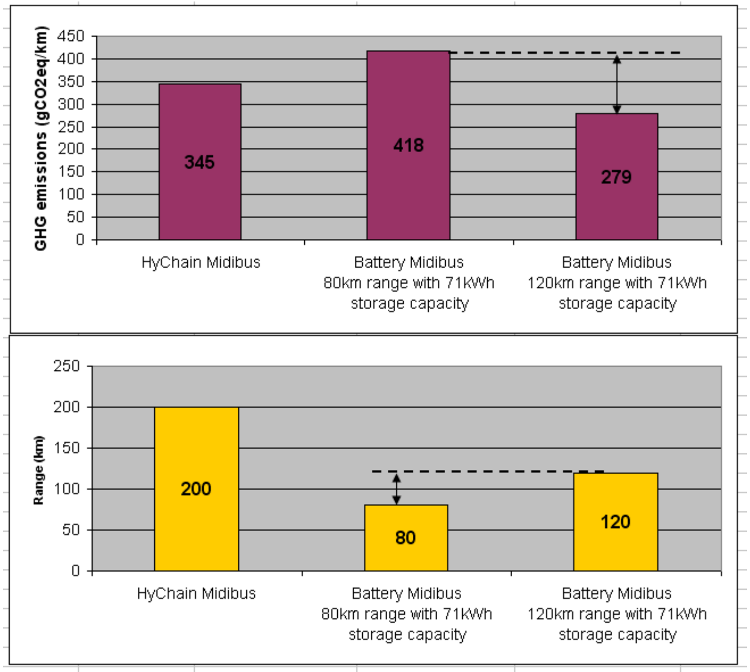



**Figure 5: Hychain and reference electric midibus range and corresponding GHG emissions.**

HYCHAIN's Explorative Environmental Impact Assessment aims at identifying the major impacts related to the life-cycle of HYCHAIN applications from production to decommissioning and disposal. The assessment will be restricted to those parts of the HYCHAIN Vehicles that markedly differ from the reference vehicles (ICEs and Electric vehicles).

The study of environmental impacts will focus on:

- fuel cell manufacturing
- manufacturing of hydrogen storage and distribution equipment
- disposal or recycling of the storage technologies and fuel cells after their life time.

The environmental aspects assessed include the use of fossil and primary energy, consumption of scarce materials such as platinum and yttrium, GHG emissions as well as other pollutant emissions ($NO_x$, $SO_2$, CO, PM, NMVOC, …) and their associated environmental impacts.

The EEIA study is in the process of collecting and processing the data related to the manufacturing processes of all components. First results will be presented at the conference.

## 6 First Results of the User Perception

The first inquiries on user perception started in the early fall 2009 with the midi-bus drivers located in the Emscher-Lippe region. The issues within the driver questionnaire cover personal experiences satisfaction with the bus, safety and maintenance aspects of the vehicle, training units and preparations courses, attitudes and knowledge and finally sociodemographic data. The sample insisted of 32 male drivers with an average age of 45.29 years and a solid experience as a bus driver of more than 10 years for 96.9% of all respondents. At the time the survey was conducted, most of the drivers drove the vehicle on a regular basis of several times a week (42%) or several times a month (36%).

As one example of the results, Figure 6 shows the drivers' satisfaction with the midi-bus overall performance. 44% of the drivers are satisfied with the vehicle's overall performance (14 drivers), yet 22% of the interviewees declare themselves to be rather unsatisfied (7 drivers), while one third were undecided (10 drivers). Due to the fact that the buses were operated in regular service from the beginning, these results are quite acceptable.

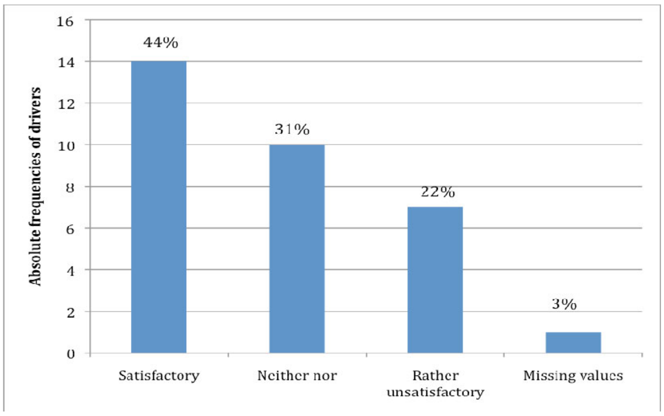



**Figure 6: Frequencies of drivers' satisfaction with the midi-bus overall performance (n=32).**

## 7 Conclusions

In sum, the HYCHAIN project is in the process of assessing the data resulting from daily operation of the vehicles and associated hydrogen across five different dimensions: technical, economic, safety, environmental and social. Based on this assessment, a forecast of HYCHAIN MINI-TRANS evolution, as well as innovation and policy-oriented conclusions will be carried out at the end of the project.

The presented poster gives insights into the first results of the five assessment dimensions, focusing mainly on the technological, environmental and user perception assessment. At the time of poster presentation, further data on the deployment of most vehicles will be included into the assessment. The outlook for future demonstration and early market initiatives will be analysed in the light of these results.

SA Strategic Analyses
SA.1 Research & Development Targets and Priorities
SA.2 Life-Cycle Assessment and Economic Impact
SA.3 Socio-Economic Studies
SA.4 Education and Public Awareness
SA.5 Market Introduction
SA.7 Regional Activities
SA.8 The Zero Regio Project

# Education and Public Awareness

**Thorsteinn I. Sigfusson**, University of Iceland and Innovation Centre Iceland, 112 Keldnaholt, Reykjavik, Iceland
**Bernd Emonts**, IEF-3, Forschungszentrum Jülich, D-52425 Jülich, Germany

**Abstract**

Around the turning of the millennium there was a strongly felt world movement towards the utilization of hydrogen energy. It was clear that one of the main tasks to address worldwide was the one of public awareness and education.

In the first years of the millennium, education was seen as crucial to the emerging global transition, providing political leaders, technical specialists, and laypeople with the knowledge necessary to play their own, appropriate roles in the transition to a hydrogen-based energy infrastructure. Education in hydrogen energy was seen as a crosscutting issue and touching upon almost all levels and individuals in society. The need to inform and educate all government officials ranging from national to local was seen as crucial; the safety and code officials; the university and college students as well as primary and secondary teachers and students together with the general public.

In the following the authors intends to briefly review some important examples of experience with education and public awareness building worldwide throughout the past decade or so. The review is by no means complete but should give the reader some insight into the subject.

# Role of Hydrogen on Engineering Education: ICHET Example

**M. Suha Yazici***, International Centre for Hydrogen Energy Technologies, 38/4 Sabri Ulker Sk, Cevizlibag-Zeytinburnu, Istanbul, Turkey

**Abstract**

International Center for Hydrogen Energy Technologies (ICHET) has been successfully supporting engineering students with practical experience on hydrogen and fuel cell systems built upon their theoretical engineering learning through classroom. A series of activities designed to increase the knowledge and awareness of engineering students and advanced-researchers has been implemented. These activities can be classified under meetings, system integration and training activities. Meeting activities include short courses, technology specific workshops and conferences, sponsorships and summer schools. System integration for prototype demonstrations forms the basis for hand-on practical learning through university-industry collaboration, demonstration activities and application specific supports. Training activities involve internships, part-time employment and laboratory educations. All these activities facilitate knowledge transfer, exchange of information at regional, national and international levels and involve academics, researchers, experts and service providers to further develop their knowledge and interest on hydrogen energy technologies.

## 1 Introduction

Implementation and widespread acceptance of hydrogen technologies at all levels will take several years of technology demonstration and educational effort. On one side politicians and policy makers are expected to take radical decisions to make hydrogen more competitive for the benefit of society and on the other side, scientists and engineers have to further come up with technological breakthroughs to advance the technology for social acceptance [1,2].

ICHET activities designed to increase the knowledge and awareness of society in whole targeting different audiences [3-5]. This is necessary to make ways toward hydrogen economy and place hydrogen energy into proper perspective for its effective and efficient implementation. Demonstrations and policy work targets government and local officials to educate and make them aware of hydrogen technologies and get commitment to advance such technologies with appropriate government policies. Engineers and scientists from various disciplines, including electrical, mechanical and chemical, are part of daily activities to implement projects to the end. Educational aspect of ICHET activities can be classified into three categories: Workshops, conferences and short courses; system integration and demonstration experience and trainings and laboratory activities (Fig. 1).

* Corresponding author, email: syazici@unido-ichet.org

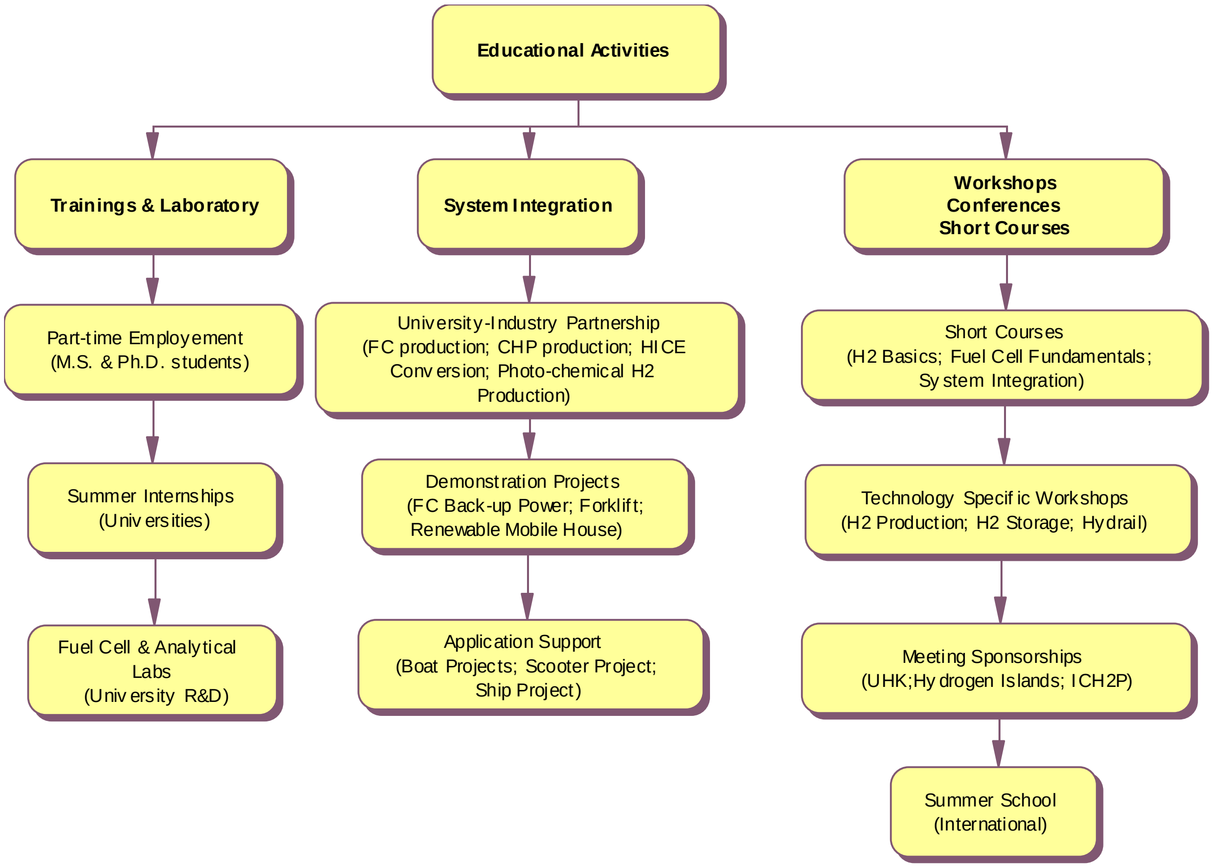



**Figure 1: Various educational activities ICHET involved.**

## 2 Workshops, Conferences and Short Courses

Conferences, exhibitions, workshops and short courses forms ideal environment for face to face learning and idea exchange. ICHET sponsored workshops and conferences provide participants with better ideas about hydrogen technologies and motivate them for further actions. Activities targeting high school teachers take place every year with ICHET sponsorships (since 2005, more than 800 physics, chemistry and biology teachers were educated and motivated to implement high school project at their schools). National activities are mainly supported under national hydrogen conferences where participants, mostly academic, get together to discuss their research and demonstration projects. These meetings are first step to introduce ICHET to university community and give them further access into ICHET capabilities. Short courses accept targeted audience with people involved hydrogen in their research or activities (Fig.2). With participation of around 40 people in each activity, hydrogen, fuel cells and the technologies around them are discussed in 2 days (Since 2007, more than 150 participants were educated on electrochemistry, hydrogen production, storage and systems research, fuel cell fundamentals-applications and system integrations with renewable (solar; PV; electrolysis) supported by hands-on laboratory activities). Throughout the courses, the practical side of the technologies is emphasized with lectures being presented in the morning followed by afternoon sessions in the laboratory where the participants could assess some techniques for themselves. Laboratory hands-on work is encouraged and given priority considering limited laboratory infrastructure in developing countries. One-week- long summer schools has been organized jointly with EC-JRC, Institute for Energy. This activity puts an international perspective into ICHET activities with participants and instructors coming from several different European countries.

Engineers were given every opportunity to participate national and international activities. Several conferences were attended as presenter or participant. ICHET exhibited at several exhibitions and engineers were allowed to participate to learn about state of the technology in various geographic locations.

**Figure 2: Students following a lecture in one of the short courses.**

## 3 System Integration

ICHET, university and industry partnerships are utilized to take R&D stage development into prototyping and eventually advancing towards commercial product introduction. Support of several universities in Turkey (METU, NU, EU, IU, SDU, GU, YU, AU) helped several M.S. and Ph.D. students to gain expertise on their subject field and helping capacity building in Turkey. Existence of several high class universities offering M.S. and Ph.D. degrees in electrical-electronics and mechanical engineering helped ICHET to recruit high quality individuals to realize projects.

Engineering students in mind, several external projects were initiated and supported with student clubs to help turning theoretical engineering knowledge into practical experience. Projects, including fuel cell boat construction with six universities, hybrid scooter and hydrogen vehicle constructions are all designed to benefit student from electrical, mechanical, chemical and even from ship-construction engineering departments.

Demonstration projects by themselves are great learning platforms to solve problems with real world applications. Fuel cell back-up power systems were installed and system diagnostics were carried out constantly to seamlessly integrate fuel cell power plant, converters, rectifiers and hydrogen supply system [6]. Forklift project required system integration knowledge and utilized diagnostics tools to identify problems. On mobile renewable house project, development of the data acquisition and monitoring system plus implementation of automatic controls for power management is done by ICHET engineers (Fig. 3). MATLAB and LabVIEW were used constantly to develop models between the parameters and energy production [7]. Automatic controls are designed and installed to optimize the storage efficiency of the system. Demonstration projects implemented in Turkey and abroad have always relied on support provided by new graduates or M.S. and Ph.D. students for system integrations, maintenance, data acquisition and analysis. Electrical engineers worked on electrical connections and software issues while mechanical engineers have maintained system for continue operation by replacing filters, faulty pieces and necessary mechanical components. Electrical and mechanical engineers were always on site to make the first move.

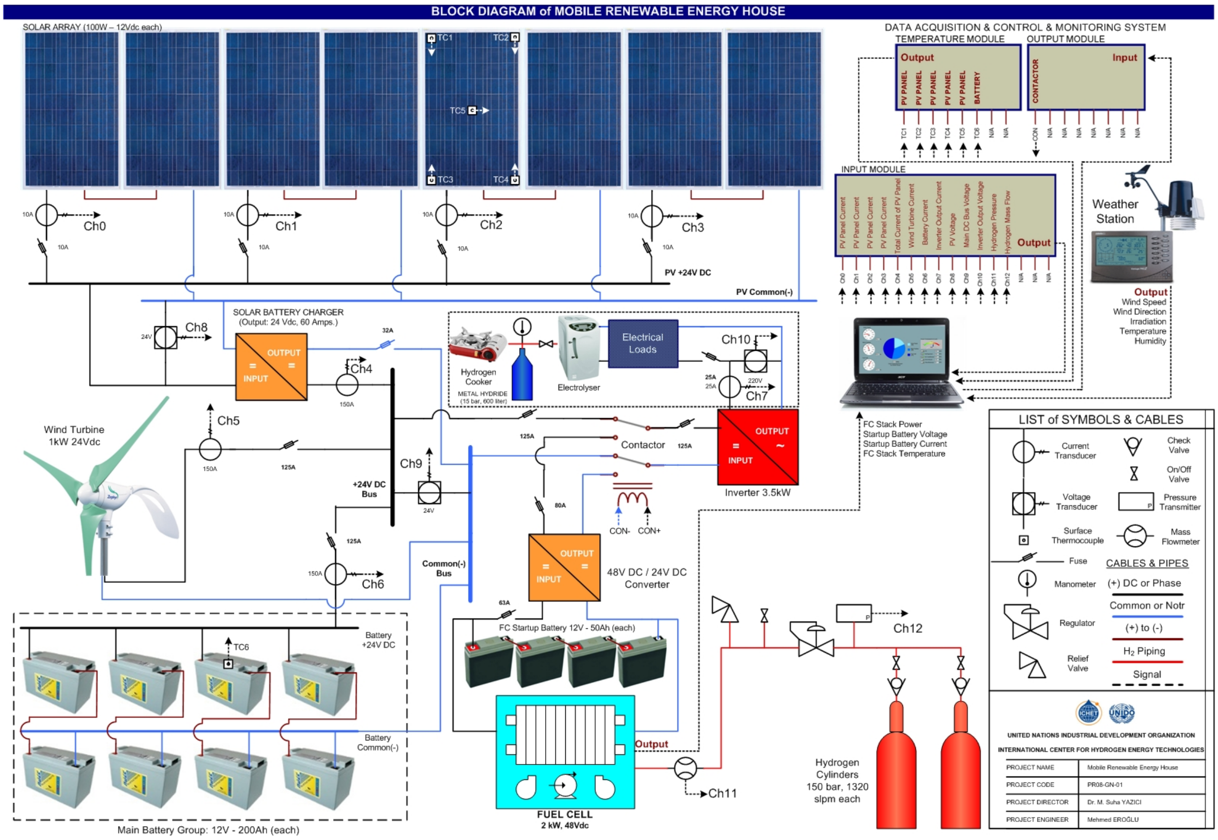



**Figure 3: Power flowchart for renewable mobile house developed by engineering students.**

## 4 Trainings and Laboratory Activities

Schools visits were the first stage to encourage engineers to take part in various activities. Presentations on several universities took place in events organized by engineering student clubs. ICHET projects were presented and discussed by fellow engineers on several occasions. Master and Ph.D. students from engineering disciples are supported part-time basis to work at ICHET helping staff on hydrogen fuel cell related activities while working towards their degrees. Since 2005, more than 70 students have been supported under this program. In the past ICHET has received visiting scientists from other institutions. ICHET had post-doctoral stays from India, Pakistan (2), Iraq, Germany, USA, Egypt and Turkey (2).

ICHET has organized several training seminars about basic technology and research topics as well as analytical equipment use. "Fuel cell integration", “Fuel cell fundamentals, engineering and applications” and "Tools for the Characterization of Materials for Energy Applications" are some to mention with wide spectrum of coverage. Each training activity accepted around 40 participants from universities, companies and government. These trainings provided theoretical background on first day and laboratory experience on the second. Extensive use of the Centre's laboratory facilities and demonstration of the project vehicles were useful in providing real hands-on experience to the participants (Fig. 4). State of the art laboratories include several a few watt to 12 kW test stations, electrolysers (500 cc/min to 1 m3/hr), various hydrogen storage options, analytical instruments such as gas adsorption analyzer, surface area and porosimetry, TGA-DSC and others.

**Figure 4: Scenes from ICHET laboratory activities.**

Under sponsorship and internship program, national and international students are given opportunity to participate in hydrogen and fuel cell related technology training and internships. Internship activities facilitate knowledge transfer, exchange of information at regional, national and international levels. Every summer ICHET accepts about 5-7 summer interns to work at ICHET. Various subjects are studied by undergraduate students during 20-30 days of stay.


**Figure 5: ICHET project advertisement.**

## 5 Conclusions

ICHET is taking its position in the hydrogen world to promote hydrogen and fuel cell technologies to the developing world through demonstrations, trainings and educational activities (Fig. 5). Preparation of human potential, next generation of scientists and policy makers have great importance for future acceptance of these technologies. More coordinated actions with global organizations will be implemented

## Acknowledgements

Financial support of Turkish Ministry of Energy and Natural Resources is greatly acknowledged.

## References

[1] Barbir, F., Transition to renewable energy systems with hydrogen as an energy carrier Energy, Volume 34, Issue 3, March 2009, Pages 308-312

[2] Neef, H.J., International overview of hydrogen and fuel cell research Energy, Volume 34, Issue 3, March 2009, Pages 327-333

[3] Yazici M.S., Hydrogen and fuel cell activities at UNIDO-ICHET, International Journal of Hydrogen Energy, Volume 35, Issue 7 , Pages 2754-2761 (2010).

[4] Yazici, M.S., Hydrogen and fuel cell education activities at UNIDO-ICHET, Extended Abstract, 17th World Hydrogen Energy Conference, WHEC2008, June 15-19, 2008, Brisbane, Queensland, Australia

[5] ICHET web site: www.unido-ichet.org

[6] Yazici, M.S., Hydrogen and Fuel cells: Solutions to Energy & Environmental Problems, Extended Abstract, 14th International Energy and Environment Fair & Conference, ICCI2008, May 15-17, 2008, Yesilkoy, Istanbul

[7] Eroglu, M., Yazici, M.S., A Stand-Alone Mobile House using PV/Wind/Fuel Cell Hybrid Power System HYSYDAYS 2009 - 3rd World Congress of Young Scientists on Hydrogen Energy Systems

# Contributions to Training and Education Made by Institutional Research

**B. Emonts**, **D. Stolten**, Forschungszentrum Jülich GmbH, Institute of Energy Research – Fuel Cells (IEF-3), Germany

In order to pave the way for the dissemination and success of hydrogen and fuel cell technologies, targeted training and further education is indispensable. This is the reason why this topic is also an important building block in current research, development and demonstration programmes. Today, the topic of hydrogen and fuel cells is already well established in training and education programmes in universities and third-level institutions, as well as in the education sector in general. Forschungszentrum Jülich has been active in this area for a number of years. Three research institutes are involved, each working in the area of their research and development expertise: IEF-1 focuses on materials synthesis and processing, IEF-2 on microstructure and the properties of materials, and IEF-3 on fuel cells. Work devoted to the solid oxide fuel cell (SOFC), high-temperature polymer electrolyte fuel cell (HT-PEFC) and the direct methanol fuel cell (DMFC) is supported by other project groups involved the areas of systems analysis (IEF-STE), project coordination (IEF-PBZ) and joining techniques and assembly (ZAT). A total of 160 people at Forschungszentrum Jülich are involved in the research and development of fuel cell technologies for specific applications. The most important contributions made by research at Jülich to training and further education addressing issues associated with future hydrogen and fuel cell technologies will be presented in the following sections.

## 1 University Education

In line with Jülich's guiding principles, scientists at Jülich are also involved in teaching activities at universities in parallel to their research and development work [1]. Within the framework of this so-called Jülich model, IEF boasts three such joint appointments with North Rhine-Westphalian universities. Prof. Dr.-Ing. Detlef Stolten and Prof. Dr.-Ing. Lorenz Singheiser each hold a chair at RWTH Aachen University. Prof. Dr. rer. nat. Detlev Stöver is head of department at Ruhr University Bochum. Two chairs at Aachen University of Applied Sciences, Division Jülich, are held by Prof. Dipl.-Ing. Ludger Blum and Prof. Dr.-Ing. Ralf Peters. Furthermore, PD Dr. rer. nat. Werner Lehnert lectures at the University of Ulm. Two other teaching positions at Aachen University of Applied Sciences, Division Jülich, are held by Dipl.-Ing, Dipl.-Wirt.Ing. Thomas Grube and Dr. Ir. Willem J. Quadakkers.

The spectrum of topics taught ranges from the fundamentals of science and theoretical modelling and simulation methods to detailed technical knowledge and the characterization of technical applications. In total, ten lectures and four seminars are taught each semester, usually in the form of double periods. Lecturers also provide their students with additional material on the subjects taught. This comprehensive documentation containing illustrations, tables, and diagrams, for example, helps to prepare students for the compulsory examinations. Table 1 provides an overview of the courses taught at universities by members of staff at IEF-3.

**Table 1: University courses taught by members of staff at IEF-3 (V = lecture; Ü = seminar)**

| Name | Topic | Type/hours | semester | University |
|---|---|---|---|---|
| **Prof. L. Blum** | Brennstoffzellen – Die Zukunft der dezentralen Energieversorgung!? | V/2 | WS | Aachen Univ. of Applied Sciences, Division Jülich |
| | Fuel Cells – The Future for Dispersed Power Supply!? | V/2 | SS | |
| **Prof. Dr. R. Peters** | Basics and Applications of Chemical Reaction Theory – Simulation of Dynamic Processes in Energy Systems with Matlab/Simulink | V/2<br>Ü/2 | WS | Aachen Univ. of Applied Sciences, Division Jülich |
| **Prof. Dr. L. Singheiser** | Werkstoffe der Energietechnik | V/1 | WS<br>SS | RWTH Aachen University |
| | Neue Werkstoffe für energietechnische Anlagen | V/1 | WS<br>SS | RWTH Aachen University |
| **Prof. Dr. D. Stöver** | Hochtemperatur-Brennstoffzelle – SOFC – Solid Oxide Fuel Cell | V/4 | WS | Ruhr University Bochum |
| **Prof. Dr. D. Stolten** | Grundlagen und Technik der Brennstoff-zellen | V/2<br>Ü/2 | WS | RWTH Aachen University |
| **T. Grube** | Basics and Applications of Chemical Reaction Theory – Simulation of Dynamic Processes in Energy Systems with Matlab/Simulink | Ü/2 | WS | Aachen Univ. of Applied Sciences, Division Jülich |
| **PD Dr. W. Lehnert** | Brennstoffzellen – von den Grundlagen bis zur Anwendung | V/2 | SS | University of Ulm |
| | Elektrochemische Verfahrenstechnik | V/2 | WS | |
| **Dr. W.J. Quadakkers** | Werkstoffe in der Energietechnik | V/3 | WS | Aachen Univ. of Applied Sciences, Division Jülich |
| | Materials in Energy Systems | Ü/3 | SS | Aachen Univ. of Applied Sciences, Division Jülich |

The number of students participating in the individual courses each semester varies between ten and fifty. The scientists working at the institutes concerned with fuel cell development also play an important role supervising term papers, diploma dissertations and PhD theses. On average, around nine diploma and master dissertations and seven PhD theses are completed every year on topics dealing with fuel cells.

## 2 Conferences and Workshops for Science and Industry

Modelling experts at Jülich organized the international MUSIC Conference in March 2008, attracting participants from Canada, the United Kingdom and Germany to Forschungszentrum Jülich. MUSIC stands for “Multi-Scale Integrated Fuel Cell Model”. It focuses on the modelling of different types of fuel cells on various scales - from the stack right down to sub-cell components. The favoured tool for this task is the CFD software OpenFOAM, which is also used at Forschungszentrum Jülich. Within the framework of the conference, trainers from Wikki Ltd presented the software, showing participants the tool’s wide-ranging functionality. Compared to the other CFD tool used at Forschungszentrum Jülich - FLUENT - the open-source software OpenFOAM not only offers the user many of the most important features of FLUENT, but it also has good potential to be extensively expanded - a feature that is often essential in the field of fuel cells. Last but not least, OpenFOAM software promises compatibility for applications on supercomputers, which is of particular interest to scientists at Jülich.

For the fourth time, a representative of Forschungszentrum Jülich acted as chairperson of the German Hydrogen Congress when Professor Stolten took the chair for the fourth congress in 2008. The scientific and technical side of the conference was aimed at representatives from politics, industry and science, and included two one-day events with plenum and parallel sessions, company stands and poster presentations. In relation to the fields of energy, technology and industry, the conference took a detailed look at the path and role of hydrogen in the energy economy [2]. The overwhelmingly positive response to the last event and the encouragingly large number of participants confirmed the congress’s function as a scientific, technical and strategic discussion platform.

The coordination of the Lucerne Fuel Cell Forum rotates on an annual basis among well-established European scientists. Professor Stolten was responsible for the 2nd European PEFC Forum in 2003 [3], while Dr. Steinberger-Wilckens took over the chair for the 8th European SOFC Forum in 2008 [4]. The forum targets an international specialist audience and runs over the course of four days. It is accompanied by scientific and technical stands and poster presentations.

In cooperation with representatives from European research institutions, Jülich scientists have been organizing workshops since 2004 with the objective of sharing and discussing the latest findings in SOFC research and development. The topics change from event to event and range from materials science and modelling to cell tests and characterization as well as system components (BoP) and complete systems. In twenty-minute presentations, representatives from industrial organizations and institutional research report on the progress and current status of research and development.

## 3 Summer Schools and Tutorials

For university students, the Energy Research Area at Forschungszentrum Jülich organizes occasional seminars and summers schools in cooperation with the universities. Depending on the type of cooperation, these events are held at the partner university or at Forschungszentrum Jülich. In autumn 2008, for example, a four-day master-class course was held on “Renewable Energies” at the University of Applied Sciences in Eberswalde. This course focused on climate change and possible measures to reduce climate-gas emissions. Jülich scientists gave presentations on topics such as the role of fuel cells as clean drive alternatives in the transport sector of the future. Two years previously Jülich scientists coordinated the Berlin autumn seminar 2006 on fuels and drives for the future in cooperation with university representatives from TU Berlin. Students and staff of the university in the field of automotive engineering participated in presentations and discussions on hybrid and hydrogen drive systems over the course of five days. The event also involved a technical excursion to the hydrogen filling station operated by the Clean Energy Partnership (CEP).

Jülich SOFC researchers together with representatives from other European research institutions have been organizing annual summer schools since 2004. These schools are usually held over the course of five days and are dedicated to specific R&D topics in the area of solid oxide fuel cells (SOFCs). The presentations and papers given by scientific experts are aimed at PhD students and young scientists. The synergy of presenting subjects in depth in an easy-to-understand manner provides those new to the field with an opportunity to get to grips with the basics of the R&D topic.

From 2001 to 2008, Professor Stolten held the Fuel Cell Tutorial in the run-up to the annual Fuel Cell Forum in Lucerne. As an internationally recognized fuel-cell expert, he introduced young scientists to the fascinating world of fuel cells and taught interested individuals working in scientific and technical fields the expert knowledge they were lacking. The tutorial simultaneously functioned as a specialist introduction to the conference week with papers on current findings from fuel cell research and development. In the relaxed atmosphere of a small working group, all of the questions raised by the participants were answered. Every participant received accompanying documentation for the tutorial including numerous useful illustrations, tables and diagrams. This documentation reflects the broad-based experience that Professor Stolten has in the field of solid oxide and polymer electrolyte fuel cells from the perspective of industry, research and science.

## 4 Work Experience for School Students

The work experience programme aims to address the requirements and requests of each group of secondary-school students aged between 15 and 18, while simultaneously reflecting the scientific and technical resources of the supervising working group. Work experience lasts between one and two weeks. At the beginning of their work experience, school students are given an introduction to fuel cell technology, a tour of the laboratories and instructions on safety. The members of the group then spend around a day with each working group gaining insights into laboratory work. The tasks assigned to secondary-school students during work experience range from shadowing technical and scientific staff at the institute to supervised independent work on selected practical projects. The school students learn the specific features of the different types of fuel cells and gain experience in job-related issues that arise when working in a scientific laboratory environment. On average every year, 12 to 15 school students take part in the work experience programme, which runs prior to the Easter and autumn holidays.

## 5 Information Events

The range of events organized in relation to further education and the provision of information is just as diverse as the needs of the groups themselves. In order to adequately meet the demands made on a particular research institute for training and information, a variety of different events are organized by Forschungszentrum Jülich.

### 5.1 Seminars for secondary-school students and teachers

Upon request, Forschungszentrum Jülich organizes introductory seminars for secondary-school students and teachers on the topics of hydrogen and fuel cells in order to provide participants with an intelligible overview. Seminars generally last between one and six school periods. When conducted at Forschungszentrum Jülich, they also include a one-hour laboratory tour. In the past few years, a number of seminars were held both at IEF-3 and in surrounding schools. On average, between 25 and 70 secondary-school students and teachers take advantage of the organized events each year.

Within the framework of the 4th German Hydrogen Congress in 2008, Jülich researchers organized a further education information day on the topic of "hydrogen and fuel cell technology" for secondary-school students, university students and teachers (see Figure 1). The day-long event held in Messe Essen provided the some 150 participants with interesting information on basic scientific and technical concepts as well as application-oriented systems. An overview of training opportunities and job descriptions in the area of "hydrogen and fuel cells" was also presented.


**Figure 1: The further education information day in Essen, February 2008.**

### 5.2 Information events for small and medium enterprises in the region

Over the last number of years, requests have often been received from companies in the region for information events on current issues in the field of energy technology. The organization and content of such events is targeted at the needs of the participants. In the past, for example, a number of round-table discussions, workshops and seminars have been held on the topics of hydrogen, fuel cells and electromobility with up to 100 participants.

### 5.3 Information events and visits to the institute for interested members of the general public

In order to promote a positive image of Jülich R&D activities in the public sphere, Forschungszentrum Jülich organizes information events and visits to the various institutes involved in the different R&D areas for interested members of the general public. Within the framework of such events, fuel cell technology has proven itself to be particularly popular. Each year a good 80 events are organized, and in 2008 around 1,400 participants learnt more about fuel cell technology. In general, the visit to IEF-3 is split into two parts: an introductory presentation by a competent young scientist, followed by a guided tour of the laboratory.

## 6 Schools Laboratory

The Jülich Schools Laboratory (JuLab) has set itself the task of introducing students to the world of hydrogen and fuel cells by encouraging them to conduct their own experiments [5]. Experiments have been developed for this purpose, and students perform them in order to find theoretical and practical solutions to technical tasks. Using an incomplete model vehicle with a fuel-cell drive system, school students work on properly completing the vehicle in JuLab, the Vocational Training Centre workshops and the Institute of Energy Research - Fuel Cells (IEF-3). Any components required are fabricated by the students themselves under supervision and tested for application. In performing this work, they gain insights into a variety of different jobs such as that of a scientist, laboratory assistant, mechanic and electronics engineer.

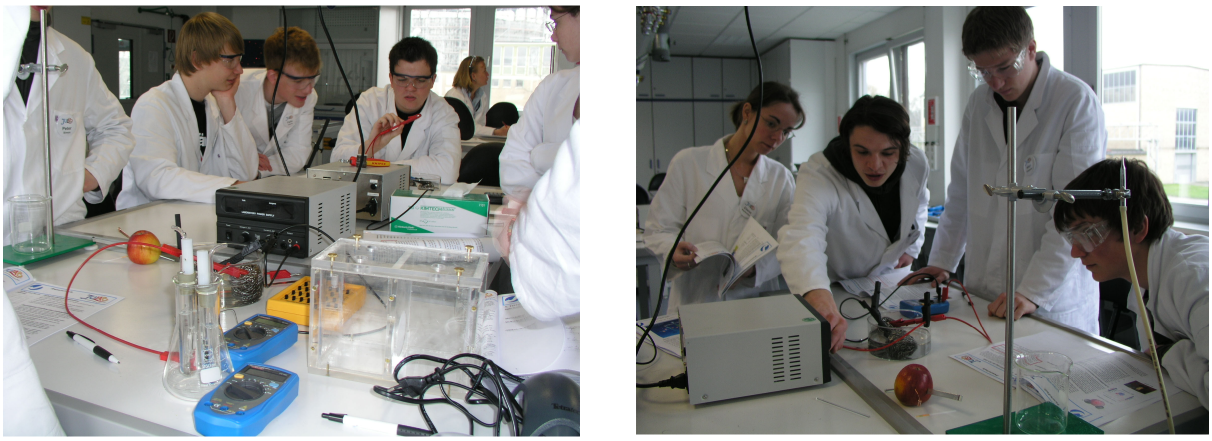


**Figure 2: School students conduct experiments in the Schools Laboratory on the topics of "hydrogen" and "fuel cells".**

Experiments are conducted under supervision in the well-equipped Schools Laboratory (see Figure 2). As students need to be familiar with conducting experiments from chemistry and physics classes, they must be aged 16 or over. The programme usually takes around one week.

## 7 Collaboration with External Organizations

More and more attention is being devoted to designing, launching and implementing training and further education measures and qualification programmes on the topic of “fuel cell technology” both in the manufacturing industry and the relevant educational establishments. In order to cater for this demand, special initiatives have been launched. The combination of specialist technical knowledge and existing opportunities provide an excellent basis for collaboration. Forschungszentrum Jülich, for example, works very closely with the Fuel Cell Qualification Initiative, which aims to disseminate information on future fuel cell applications in order to pave the way for a smooth market introduction. This objective is accomplished by concrete involvement in development projects in terms of information provision and qualification measures.

Furthermore, Forschungszentrum Jülich collaborates with institutions in the training and further education sector. Jülich experts, in cooperation with the educational organization RAG Bildung and the entrepreneur centre Zukunftszentrum Herten, hold lectures for the Fuel Cell Education and Training Centre Ulm aimed at interested individuals working in the skilled trades, industry, research and education.

Together with the University of Bonn and Northwestern University Chicago, Forschungszentrum Jülich developed a summer school programme on “renewable energy”. The school is due to be held in 2010. In addition to topics from energy policy, the scientific and technical aspects addressed by Forschungszentrum Jülich are also on the agenda of courses for qualified students offered at American universities. Jülich experts are often invited to give guest lectures at participating American universities. Suggestions have been made that the programme should be expanded to include aspects such as work experience and internships.

## 8 Summary

In order to pave the way for the dissemination and success of hydrogen and fuel cell technologies, targeted training and further education is indispensable. This is the reason why this topic is also an important building block in current research, development and demonstration programmes. Today, the topic of hydrogen and fuel cells is already well established in training and education programmes in universities and third-level institutions, as well as in the education sector in general. Forschungszentrum Jülich has been active in this area for a number of years.

Research scientists at Forschungszentrum Jülich teach and lecture in higher education institutions. One of the results of combining scientific and technical work with teaching activities is that comprehensive training material reflecting the current state of the art is made available. International comparison has shown the excellent position held by Jülich fuel cell research. As a result, the scientists involved receive numerous invitations to chair and coordinate scientific conferences and tutorials. Furthermore, experts at Jülich are also involved in summer schools and other training and further education measures. Forschungszentrum Jülich offers secondary school students work experience and hands-on project-related experience at the Schools Laboratory. Both of these programmes are well received. Cooperation with external organizations in terms of information events and training and further education as well as the preparation and implementation of qualification projects rounds off activities at Jülich in the area of training and further education over the last few years.

**References**

[1] IEF-3 Report 2009, Basic Research for Applications, Schriften des Forschungszentrums Jülich, Reihe Energy & Environment, Volume 45 (2009), ISBN 978-3-89336-585-2

[2] Der 4. Deutsche Wasserstoff Congess 2008 - Tagungsband, Detlef Stolten, Bernd Emonts, Thomas Grube (Hrsg.), Schriften des Forschungszentrums Jülich, Reihe Energy & Environment, Volume 45 (2009), ISBN 978-3-89336-533-3

[3] 2nd European PEFC Forum 2003, Detlef Stolten, Bernd Emonts, Ralf Peters (Eds.), Proc. Volume 1 + 2 (2003), ISBN 3-905592-13-4

[4] 8th European SOFC Forum 2008, Proc. (2008), CD

[5] http://www.fz-juelich.de/projects/index.php?index=644/

# Market Introduction of Hydrogen Technology: the Evolution of the Global Education and Vocational Training Markets

**Ake Johnsen**, **Uwe Kueter**, h-tec Wasserstoff-Energie-Systeme GmbH, Germany

## 1 Introduction

In the coming years the rising demand for energy security – driven by the international struggle for resources, the increasing scarcity of fossil fuels and energy security, as well as concerns about global warming and pollution - will continue to expand the market for green energy in general and hydrogen energy in particular. These trends are reflected in the increasing number of financial investments in this field from both state agencies and corporations around the world.

Hydrogen technology is particularly well-positioned because of its ability to complement other emerging clean technologies such as wind and solar power, which have seen immense increases in the last 5-10 years worldwide. Hydrogen technology can be the all-important "buffer" which allows energy to be generated when possible, stored until needed, and used without producing harmful emissions.

Many governments provide incentives for green technologies, and make a point of including fuel cell technology, which is widely seen as a bridging technology between today's fossil fuel economy and any future hydrogen economy. In other words, fuel cell technology is already seen as being fuel agnostic, environmentally friendly, economically efficient, and technologically flexible. Fuel cell products are in the early stages of commercialization, as witnessed by the availability of consumer products such as auxiliary power units for camping, and products based on military prototypes. In general, hydrogen technology can be readily applied in portable and stationary applications, in many cases making use of the existing gas network, and of course – in perhaps its most visible application – in the automotive and transportation sector.

Yet in order to be a viable complement to and ultimately a replacement for fossil fuels, a future hydrogen economy needs further breakthroughs and wider popular adoption of the technology; hydrogen technology is both fuel flexible and application flexible. In certain jurisdictions, principally Japan, the USA, and Germany, education is leading these developments. The sales data for educational products are highly correlated with the numbers of demonstration programmes and early-stage commercial products that are sold in regions that have strong government support for the technology.

The introduction of hydrogen technology will affect aspects of education at many levels. Occupational opportunities will expand. Key aspects of curriculum content in schools and universities will be adapted to new challenges. Advanced vocational training and research will have to supply answers to the challenges posed by hydrogen technology. The presentation will review the past decade of development and offer an introduction to the rapidly expanding market for educational and demonstration fuel cell products – primarily by means of a case study of the German company h-tec Wasserstoff-Energie-Systeme GmbH (h-tec Hydrogen Energy Systems).

## 2 h-tec

h-tec Hydrogen Energy Systems was founded in February 1997. At that time, the technology for industrial fuel cell applications was aimed at small, highly-specialized markets and required substantial funding. While studies had shown that, in theory, fuel cells could provide a new energy supply, this was economically impractical. Therefore, the initial batch of custom-made fuel cells and electrolysers was created with the educational market in mind.

At the Hanover Fair in April 1997, h-tec gave the first public display of its first full array of fuel cells and electrolysers. Today, the multifaceted educational product lines subsequently developed by the h-tec Education division still constitute the core business of the company. h-tec was the first company to offer fuel cells and electrolysers based on proton exchange membrane (PEM) technology, and h-tec's products are exported worldwide to be used in schools, colleges, technical colleges, universities, and by companies and institutes to demonstrate this new technology to their customers and to the public. In 2009 h-tec sold about 11,500 products, of which 85% were exported.

In 1999, development work started on the business division of industrial applications (h-tec Industrial). To this end, fuel cells and higher performance electrolysers have been developed, with the goal of being able to offer the best price/performance ratios and associated high quality standards in targeted service areas and markets.

## 3 Evolution of Hydrogen Technology Education Markets

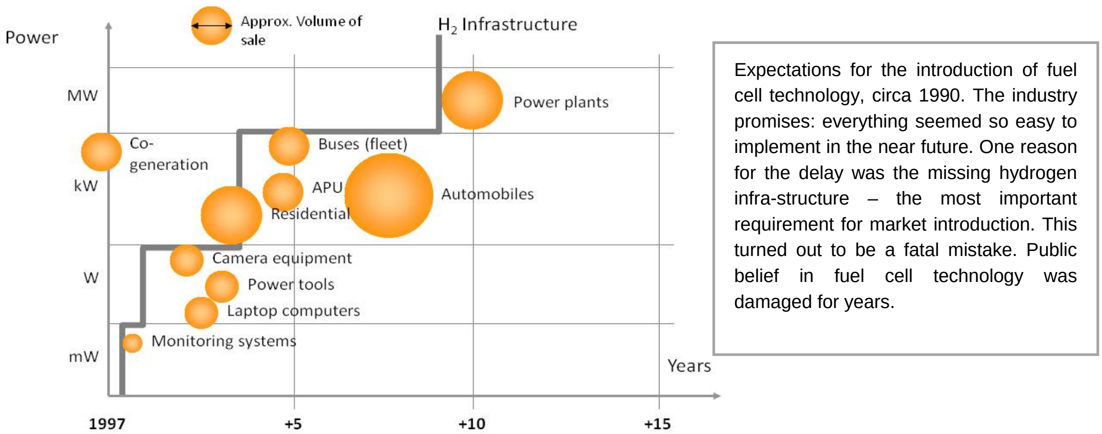



**Figure 1: Expectation in the fuel cell market in 1997.**

Interest in fuel cell technology increased rapidly throughout the 1990s. Automobile manufactures sought an alternative low-emission, high-efficiency energy conversion device that could be implemented at a reasonable price. In addition, heating system manufacturers became interested in alternatives to heat engines. In 1997, conventional wisdom held that in six years fuel cell technology would be ready for markets and available in cars, heating systems, and many other applications in daily life.

However, at this time, fuel cells were little more than laboratory prototypes. Nevertheless, the growing interest in fuel cell technology generated a need for educational and demonstrational products. The first teaching systems were customised products, mainly for public outreach events run by institutions such as municipal utility companies.

Bespoke production led to high unit prices: e.g. €3,500 for an alkaline solar hydrogen system with one watt output. Today a solar hydrogen system with the same output costs about 170 €, a fall in price of some 95%.

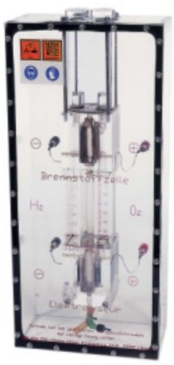


**Figure 2: Teaching system of 1995 with alkaline electrolyser and fuel cell(Source: h-tec GmbH).**

**Figure 3: State-of-the-art Solar-Hydrogen-Model for classroom instruction (Source: h-tec GmbH).**

**Figure 4: Sales partners h-tec worldwide.**

Today the market for educational hydrogen technology systems is highly competitive, with multiple participants from Germany, and a recent entrant from Singapor with production in China. Furthermore, there is a tendency towards more and more specialisation and a fragmentation of the target market into subcategories: e.g. fuel cell systems for schools, for universities, for vocational training of automobile mechanics, for the toy market, etc.

## 4 Correlation of Education and Outreach with Successful Implementation of Hydrogen Economy

h-tec experience has shown that the market for educational and demonstrational fuel cell systems correlates very closely with market development for industrial fuel cell technology. For instance, major industry players in North America, Asia and Europe are currently preparing for market introduction of commercial fuel cell products, and as can be seen in Figure 5 below, the level of market interest and penetration correlates with the historical sales figures of educational systems. Clearly, this correlation reflects a relationship with at least two sides: societies with interest in hydrogen technology are more likely to fund purchases of educational fuel cell materials, and societies where students have been trained with fuel cell technology are more likely to be able to support such an industry. There are undoubtedly other interrelationships as well, but the overall correlation is quite striking.

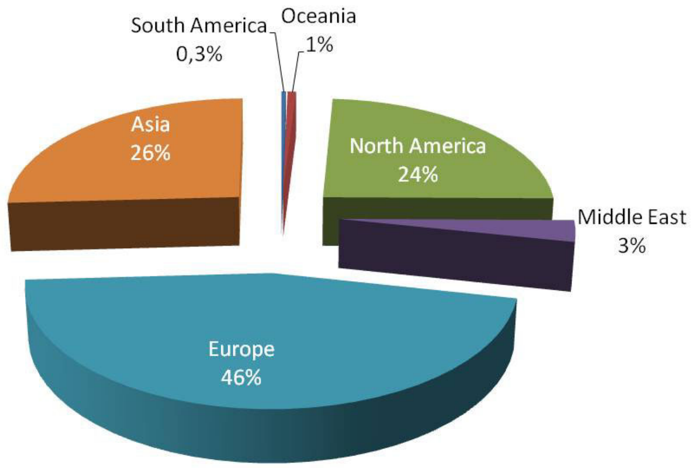
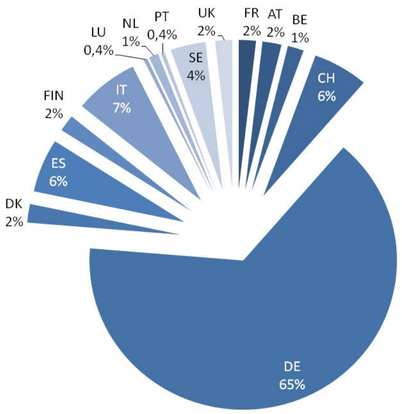


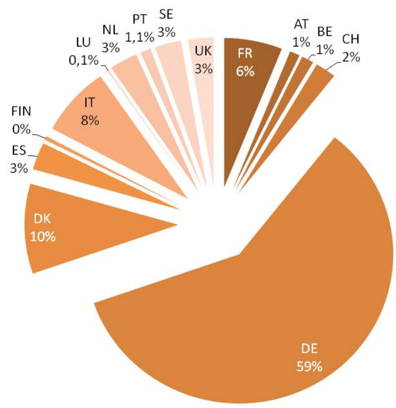

**Figure 5:** **Geographical sales breakdown of h-tec education products.**

This correlation is particularly interesting, given the difficulty of finding accurate indicators about commercial fuel cell technologies. Companies in this field are typically highly restrictive with information when asked about, for example, manufacturing capability or a breakdown of development and production costs. However, h-tec has found that to get an impression of the economic situation regarding the progress of fuel cell industries worldwide, it is sometimes also meaningful to have a closer look at the market for educational systems and services in specific countries. The number of educational systems sold is strongly correlated with the state of the industrial reality and finally with the number of commercial units that are actually installed.

As seen in the Figure 6 below, within the European market Germany is far ahead in the research and development of fuel cell systems and fuel cell powered applications. There is a particular concentration of expertise in North-Rheine-Westphalia, as this region is supported by an exceptionally well positioned network which supports its industry with a wide range of outreach activities, not to mention industrial support programs.




Installed FC in Europe - Rated Power (kW)
Source: http:/www.coretecventures.com




Sold Educational Systems of h-tec in Europe
Source: h-tec GmbH

**Figure 6: Correlation of Installed stationary systems and markets for educational products.**

## 5 Conclusion

In conclusion, our experience with the educational and industrial markets for hydrogen technology shows that the demand for technical education and demonstration products correlates strongly with the state-of-the-art technology, local and state government support, significant academic activity, and not least the amount of installed capacity. There is clearly a feedback loop between the educational and commercial worlds: interest in a technology drives demand for teaching, and interested students with a strong technical background go on to become the engineers and developers of the next phase of technological innovation. We have already seen this, even in the relatively young field of commercial fuel cells. The renaissance of fuel cell technology in the 1990s and increasing public awareness of the technology generated a demand for educational products for use in schools, universities and vocational training. At the same time, organizations realized the need for public education and the demonstration of hydrogen technology in general for companies' PR activities. h-tec stepped in to fill that demand. And now, the first generation of hydrogen researchers trained in the 1990s and early 2000s are contributing to the next wave of hydrogen technology development and commercialization. Proving causality is difficult, but if educational fuel cell activity really is a leading indicator for the commercial fuel cell industry, investment in the educational market should be an effective method of encouraging future adoption of hydrogen technology, and analysis of the educational market could show where to expect untapped commercial potential.

# New Hydrogen Outreach Program for Education (New HOPE): An American Case Study

**Mary-Rose de Valladares**, M.R.S. Enterprises, LLC, USA

## 1 Introduction

From 2006-2008, the progressive and committed New York team consisting of the New York Energy Research Development Authority (NYSERDA), the New York Power Authority (NYPA) and the Long Island Power Authority (LIPA) supported delivery of New HOPE (Hydrogen Outreach Program for Education) teacher training workshops to over 300 New York State high school science and technology teachers. These teachers will impact some 150,000 students over the next five years.

The teacher training was developed and delivered by M.R.S. Enterprises, LLC and its HOPE team. Training occurred in full day workshops that featured hands-on activities, including construction of a fuel cell vehicle from everyday materials. Workshop topics spanned the full range of learning in hydrogen production, storage, distribution and utilization, as well as fuel cells. Participating teachers received the New HOPE Pilot TM, a user friendly curriculum with one-day, one-week and enrichment lesson plans. They also received two companion videos and two kits for classroom use.

This American case study in hydrogen outreach features valuable lessons learned that can contribute to your near-term hydrogen and fuel cell education and teacher training efforts, as well as the larger transition to a hydrogen-oriented society.

## 2 The Challenge

There is widespread agreement that lack of education is a barrier to introduction and advancement of hydrogen in the economy. Today's teachers and their students -- tomorrow's consumers and citizens -- are clearly essential to our energy future. Experience suggests that one of the best ways to reach students is through their teachers. As a vehicle for technology transfer, it is the teachers who will educate students in hydrogen science and technology. But who will teach the teachers and how will the training be delivered?

## 3 The New York State Response

In the United States, New York State provides energy education through its Energy $mart Students Program. New York State has developed a Hydrogen Roadmap that features outreach and education because this state recognizes that lack of education is a barrier to introduction and advancement of hydrogen. New York State's hydrogen energy solution is called The New HOPE Pilot: the Hydrogen Outreach Program for Education.

The original M.R.S. HOPE Pilot TM, chartered by the U.S. DOE, was developed to teacher secondary students about the potential and benefits of hydrogen as a fuel and energy carrier. It is available in two versions, one for high school students (14-18 years of age) and the other for middle school students (12-14 years of age). Both are integrated student/teacher curricula organized in modules that consist of several lessons. The 75 lesson high school curriculum consists of seven modules while the 30 lesson middle school curriculum is organized in five modules. Two videos are distributed with the curricula.

However, NYSERDA preferred a more compact edition of the curriculum targeted specifically to either a “one-day” or “one-week” hydrogen program for the classroom or an after-school program. Consequently, the New HOPE Pilot TM was excerpted from the original HOPE Pilot to meet these requirements. Furthermore, NYSERDA decided to target two teacher groups, science teachers and technology teachers. Therefore, two versions of the New HOPE Pilot TM were developed, one for science teachers and the other for technology teachers. In addition to being correlated with the National Science Standards, all New HOPE Pilot TM content is correlated with the New York State Math, Science and Technology (MST) standards. The science version is also correlated with the New York State “ChemCore Guide Concepts” that were formulated to better prepare students for the New York State Regent’s Examination. Lesson plans were developed for both the nominal “one-day” and “one-week” hydrogen program for the classroom as well as an after-school program.

## 4 The New HOPE Product

The Teacher Training giveaways included: curriculum, lesson plans, a video (renewable Power – Earth’s Clean Energy Destiny) although Hydrogen – the Pollution Solution was used in the classroom; an Intelligent Car Kit and Experiment Manual for all teachers; HOPEmobile kits (with everyday materials to take back to the classroom).

## 5 The New HOPE Pilot Teacher Training Workshop

The New HOPE Pilot workshop experience is a full-day affair. It begins at 8 or 9 and continues until 3:30. The format features a mixture of lecture, demonstrations and “hands-on” inquiry based activities. It includes hospitality (continental breakfast and lunch), evaluations and giveaways.

## 6 The New HOPE Team

The New HOPE team consists of three experts in hydrogen and fuel cells, and technology education: Mary-Rose de Valladares, Ken Kenyon and Ernie Ruiz. The HOPE team’s professional expertise cross-cuts hydrogen science, engineering, business and education.

## 7 Lessons Learned

This entire New HOPE teacher training process has been a continuous learning and a continuous improvement experience. The lessons learned from the New HOPE American case study are presented here for the benefit of hydrogen educators everywhere. The lessons learned are divided into four categories: Content; Approach; Supply Chain Logistics and the Delivery of Learning; and Learning Style and Participation.

## 7.1 Lessons learned: Content

Hydrogen 101

The bottom line here is science and technology. NYSERDA and its partners asked M.R.S. to deliver hydrogen "101," which includes all the basics of production, storage, distribution, safety and utilization. It also includes all the fuel cell basics, meaning principles of fuel cells, types of fuel cells and uses of fuel cells. This strategy proved effective: hydrogen educators should focus first on delivering the hydrogen and fuel cell basics.

The Role of Standards

The New HOPE Pilot curriculum is related to the national American science standards and the applicable New York state standards. For New York State, this meant correlating lessons to the "Chem Core" that govern material covered by the New York Regent's examination as well as state standards applicable to Math, Science and Technology. Correlation of learning material to national and state standards is clearly a best practice.

Differentiation by Target Group and Interdisciplinary Content

As previously explained, the New HOPE Pilot curricula are also differentiated to meet the needs of NYSERDA's two target groups, science and technology teachers. Every effort is made to gear the training to classroom realities for both science and technology teachers. Hydrogen educators should understand the needs of their target audiences and teach accordingly.

Irrespective of the target audience, hydrogen educators should be aware that the need for interdisciplinary content that goes beyond science and technology. With New HOPE Pilot training, M.R.S. provides an interdisciplinary training experience that puts considerable emphasis on the non-science areas. To adequately prepare teachers, hydrogen educators will have to provide non-science content in teacher training.

"Takeaways": Tools and Materials for Future Use in the Classroom

In order to enable teachers to utilize their training it is essential to provide tools – curricula, lesson plans, materials and kits collectively referred to as "takeaways" --- which they can take back to classroom and use. By providing takeaways, hydrogen educators have the assurance that teachers possess the tools necessary to institute a program/unit in classroom. Optimally, the takeaways should include both curricula and a fuel cell kit that supports hands-on activities.

## 7.2 Lessons learned: Approach

Hand-on Activities and the Discovery Process

Today, the prevailing pedagogy of science education holds that students must discover and experience learning through hands-on activity in order to appreciate and assimilate learning. Consequently, hydrogen educators can expect teachers to use this approach in the classroom. This means that hydrogen educators must offer "hands-on" activities and a discovery experience when teaching either teachers or students. The "hands-on" training activities should, at a minimum, engage teachers in at least one method of hydrogen production. Water electrolysis via solar energy using a photovoltaic (PV) panel is preferable but water electrolysis via battery power is a practical alternative. The hydrogen should be utilized in an energy conversion device, preferably a fuel cell, to produce electricity that can power an application. Relative to applications, a mobile vehicle is a perennial crowd pleaser.

“Talking Heads” Unwelcome

The corollary to the lesson about hands-on activities and the discovery process is the lesson that teachers do not respond well to a straight lecture format, which they refer to as “talking heads.” Demonstrations occupy a middle ground between lecture and hands-on activities. While a mix of all three approaches is optimal, the balance is critical, if not to the effectiveness of the workshop learning, at least to teacher satisfaction with the experience. This is a challenge because there is a lot of background (government policy and economics, for example) that lends itself best to the “talking heads” approach.

Classroom, Classroom, Classroom

Teachers want the workshop and the materials they use to be directly related to their classroom experience.

Beyond “discovery” to Problem Solving and Interdisciplinary Learning

The New HOPE workshop series targets science and technology teachers but the pedagogy for these groups differs in some critical aspects. As previously mentioned, the pedagogy for science education centers on discovery. In contrast, the pedagogy for technology curriculum focuses on the related area of problem solving. The New HOPE Pilot TM curricula address both disciplines and their respective pedagogies.

Organization

Organization is crucial: it is in fact difficult to underestimate the importance of organization in the workshop experience. Teachers expect master teachers and trainers to have a clear and well-organized approach to every part of any program they are delivering. Teachers also prefer to leave the training fully equipped with giveaways -- curricula and other materials (such as fuel cells and mobile devices) -- for use in the classroom.

Mobility Matters

HOPE Pilot training and curricula emphasize the automotive sector from all perspectives (science, technology and interdisciplinary). The New HOPE Pilot takes this approach because mobility, cars and driving have a tremendous appeal, especially for all young people.

### 7.3 Lessons learned: Supply chain logistics & learning delivery

More Organization

For supply chain logistics and learning delivery, organization also matters – a lot. In fact, it underlies all links in the supply chain and cross-cuts all operations. It is almost the case that there is “No detail too small.”

Planning and Marketing (don’t forget to add Marketing PPT)

It all begins with planning. Consider first the teacher’s calendar and the timing in the school year, as this can greatly affect participation. Don’t forget the role of weather. In some locations there may be a preferred workshop season. With planning comes marketing – to hold a teacher training event you have to reach your target audience and entice them to attend. They need to know why this training will be beneficial to them as classroom teachers.

Teacher participation in the United States typically requires the consent of school administrations. Therefore, teachers have to be motivated to undertake the administrative measures necessary to obtain approval.

In addition to a clear explanation of the subject matter and a brief description of the event agenda, potential participants need to know the logistic details: date, time, address, exact location and parking provisions, if any. They will also need driving and /or public transit directions. Free lunch is a draw so don't forget to mention hospitality if it will be offered. The marketing process continues till the training ends. It should also include an evaluation at the end of the training with a formal survey instrument to allow measurable teacher feedback.

Resources and the Need for Substitute Stipends

Since resources are an important issue in most schools and school districts, teacher substitute stipends may be necessary to provide for the cost of substitute teachers. These substitutes would replace the classroom teachers who are attending a training event during school time.

Facilities

To increase the likelihood of success, select a desirable location as defined by your target audience. Make sure the facilities meet the event needs in terms of space, setup and audio-visual capabilities. Sketches and descriptions of all set-ups, including seating arrangements, should be prepared well in advance. It is important to coordinate closely with the hosting facility. It is also important to understand the experience level of the hosts with the type of training being offered.

Registration

The registration system should be made as simple as possible from the user's (the teacher's) viewpoint. There should be clear provision for registration confirmation as well. The system should also include a method for notifying teachers of cancellation/postponement in the event of bad weather or other circumstance beyond the hydrogen educators' control. While no system is foolproof, the notification system may need some redundancy in an effort to ensure that registered participants are timely informed.

Electronic and Audio-Visual Equipment

Planning for Electronic and audio-visual equipment is crucial. But planning alone is insufficient: all equipment should be tested in advance of the event (the previous day if the workshop begins in the morning). In addition, because smooth operation of electronic and audio-visual equipment is essential to success, it is wise to plan for a techie to be on hand to troubleshoot in the event that problems arise during the training.

Materials, Curricula, Tools and Equipment

In moving workshop materials, tools, equipment and takeaway items, it is imperative to understand the supply chain. "Supply chain" refers to what must be moved where, when and how in order to make a timely appearance at the workshop. It is highly advisable to create a contingency plan that may be put into place in the event of a supply chain "issue."

Hospitality, i.e., "food"

And last, but not least, is food. American teachers are also food critics, so apart from the obvious need to nourish the group in the healthiest manner possible, be aware that uninteresting or sub-par food may impact the training experience and the teacher feedback. It is also wise to provide for vegetarian fare and other dietary considerations (e.g., vegan) if possible.

### 7.4 Lessons learned: Learning styles and participation

Teachers as Independent Thinkers

The New HOPE experience is that science and technology teachers are independent thinkers who are dedicated to making a difference in their students' lives through their respective disciplines. They generally exhibit strong concern for the environment as well as curiosity and enthusiasm for learning. Frequently, they also display a fair amount of skepticism about the introduction of new technology, especially technology that purports to have a life changing impact and/or entails significant change to everyday "business as usual" in the government or business worlds. Therefore, the Hydrogen educator's challenge is to manage the teachers' skepticism by building on their curiosity and enthusiasm as well as their concern for the environment. Demonstrations and displays of real life technology (ride and drives, fuel cell installations) can play a very important role in allying teachers' reservations about the viability of technology.

Teacher Formation

The teachers' formation, i.e., the discipline(s) they studied and teach, affects their participation in the training because formation relates directly to their knowledge base and skill set. This is particularly apparent in "hands-on" activities that require the use of tools and equipment.

Level of Instruction

Participation also varies by the level of instruction, i.e., middle school vs. high school. High school teachers need a more in-depth understanding of hydrogen and fuel cell technology than middle school teachers. However, even at the middle school level, American technology teachers have an engineering "problem-solving" orientation that is not characteristic of science teachers at either level.

Impact of Gender

Our observation is that gender can also affect teacher training participation. As a group, females tend to have less experience with the (non-scientific) tools and equipment employed by our technology teachers. The females also tend to want to complete tasks (e.g., a "hands-on" project) and express more dissatisfaction than males when unable to do so, which typically occurs because of time constraints. Hydrogen educators can organize training activities to take these observations into account.

MTV Teachers

Finally, going back to the "talking heads" comments, remember that teachers often don't like to sit still anymore than their MTV generation students. So this means the educators should vary active and passive activities and be sensitive to "pace."

## 8 Closing

We hope you will find the American New HOPE Pilot lessons learned helpful as you train teachers in hydrogen education. As a final thought, remember to have fun – hydrogen education is building a hopeful and sustainable future that merits celebration.

## References


[1] American Association for the Advancement of Science (AAAS). *Benchmarks for Science Literacy*. Oxford University Press. 1993.

[2] M.R.S. Enterprises. *HOPE Pilot™, Hydrogen Outreach Program for Education: an Interdisciplinary High School Science Curriculum*. Washington, D.C. USA. 2000.

[3] M.R.S. Enterprises. *HOPE Pilot™, Hydrogen Outreach Program for Education: an Interdisciplinary Middle School Science Curriculum*. Washington, D.C. USA. 2000.

[4] M.R.S. Enterprises, LLC. New *HOPE Pilot™: an Interdisciplinary High School Science Curriculum*. New York City: NYPA and NYSERDA, 2006.

[5] M.R.S. Enterprises, LLC. New *HOPE Pilot™: an Interdisciplinary High School Technology Curriculum*. New York City: NYPA and NYSERDA, 2006.

[6] National Research Council of the National Academy of Sciences. *National Science Education Standards (NSES).* Washington, D.C.: National Academy Press. 1996.

[7] New York State Board of Regents: Physical Setting/Chemistry Core Curriculum. New York: the University of the State of New York.

[8] New York State Department of Education and Board of Regents. Learning Standards and Core Curriculum – Mathematics and Science. New York: 2005.

[9] New York Energy $mart Program. http://www.nyserda.org/programs/schools/default.asp.

[10] New York State Energy Research and Development Authority. *New York State Hydrogen Energy Roadmap.* Albany, New York: NYSERDA. 2005.

# Understanding the Public Acceptance of Hydrogen Technologies in Transport: A Conceptual Framework

**Nicole Huijts**, **Eric Molin**, Delft University of Technology, The Netherlands
**Linda Steg**, University of Groningen, The Netherlands

Public acceptance is recognized as an important factor determining the success of the implementation of hydrogen, next to economic and technical factors [1, 2]. As it is widely recognized that the application of hydrogen as an energy carrier has the highest potential to be implemented on a relatively short term in transport this paper focuses on the acceptance of hydrogen technologies in this application area. In transport, the public is confronted with acceptance of hydrogen in at least two different roles. In the role of consumer, people may decide whether or not to purchase a hydrogen vehicle once they are introduced at the market. In the role of citizen, people may accept or protest against refuelling stations that are planned near their living area. Acceptance in both roles may affect the chicken-and-egg problem: without a widespread network of hydrogen refuelling stations people will not purchase a hydrogen vehicle, while widespread purchase of the hydrogen vehicles is needed in order to make the refuelling stations cost efficient.

It is not entirely clear to what extent hydrogen is accepted in different situations and which psychological factors affect this. Several studies have been conducted on hydrogen acceptance [3] many of which studied consumer acceptance of hydrogen buses. Much less research has been conducted on citizen acceptance, which includes acceptance of hydrogen refuelling stations [4]. The studies are rather descriptive in nature and not well funded in theory [5] In the few studies that are based on theory, only a single theoretical perspective, that is the theory of planned behavior, has been chosen, with the result that other determinants suggested by competing theories are not taken into account. Hence, the insight in which factors affect hydrogen acceptance is still limited. To conclude, what is largely missing is a comprehensive understanding of factors influencing consumer and citizen acceptance of hydrogen technologies in transport.

To the best of the authors' knowledge, also a more general comprehensive causal framework on citizen and consumer acceptance of new technologies that can be applied to this acceptance topic has not been developed yet. In this paper we aim to fill this gap by developing a general framework for citizen and consumer acceptance of new technologies, which is also applicable to hydrogen technology in transport. The presented framework has several functions with respect to hydrogen technology research: it helps to understand the psychological factors that influence the acceptance of the transition to a hydrogen fuelled transportation system and how these are interrelated; it can support decision making by policy makers and practitioners; it can be the starting point for acceptance research for new implementations; and finally, it will help to understand both the value and limitations of currently available hydrogen acceptance studies.

The development of this technology acceptance framework is based on several theories that are well-known in social and environmental psychology. The theories are selected based on their relevance for new technologies that have environmental or societal benefits, but at the same time carry risks and additional costs compared to common technologies, like the case of hydrogen technologies.

As a start to understanding public acceptance, we recognize that people's acceptance behavior may be motivated by different goals. Lindenberg and Steg [6] explain that goals are influencing decision making: "goals govern or 'frame' what people attend to, what knowledge and attitudes become cognitively most accessible, how people evaluate various aspects of the situation, and what alternatives are being considered." Three goals are distinguished here: the gain goal, the hedonic goal and the normative goal.

The gain goal is typically assumed to be the strongest goal in preference studies: it assumes that people base their decisions on costs-benefit analyses and choose options with the highest gains against the lowest costs. This aligns with the theory of planned behavior [7] which assumes that people's attitudes are based on the evaluations of consequences related to the object or the behavior. This theory postulates that attitudes influence intentions to act, which in turn influences behavior. In addition to attitudes, subjective norm and perceived behavioural control are also assumed to influence intention to behave and behavior. Subjective norm reflects the perceived social pressure to perform or not perform the behavior. Perceived behavioural control reflects the perceived ease or difficulty of performing the behavior. So in the gain goal-frame, people can decide to buy a hydrogen vehicle based on their evaluations of costs, risks and benefits, on what they believe other people think of buying and having the car (reflecting social costs and benefits) and on whether it is perceived to be difficult to purchase, drive and maintain a hydrogen fuelled vehicle. For example, Molin et al. [8] showed that preferences for hydrogen vehicles are influenced by costs (fuel price and vehicle purchase cost) and convenience factors (detour and range).

The hedonic goal-frame suggests that affect has the strongest impact on people's attitudes and behavior; people will base their decision on what feels best. This means that people do not merely aim to optimize the personal outcome of the technology when deciding between behavioural options, but also make decisions based on feelings. Dual-processing theories (e.g. [9]) are theories in the field of psychology that discuss the role of affect. These theories distinguish affects and cognitions assuming that these reflect two separate systems in human thinking and decision making; the impulsive system and the reflective system respectively [9]. While in the reflective system decisions are based on reasoning and logic, in the impulsive system decisions are based on associations and affect. The theory suggests that the two systems have a separate role in attitude formation, but at the same time also influence each other, which means that acceptance will be influenced by people's weighing of perceived costs, risks and benefits, as well as by emotions. Positive and negative emotions have been found to influence technology acceptance (e.g. [10]). For example, the study of Montijn-Dorgelo and Midden [11] measured the influence of associations and affect (both a sign of the impulsive system) and showed that strong associations with danger influenced perceived risks and benefits via the affective pathway.

The normative goal-frame suggests that people base their choice on what is the most appropriate thing to do; on what they think "ought to be done". This goal-frame is relevant for technologies that have an environmental or societal beneficial component. An example of acting on a normative goal-frame is that if people think that it is our personal obligation to attend to the environment, they will purchase clean vehicles like hydrogen vehicles and support refuelling stations for clean fuels. Personal norms reflect feelings of moral obligation to engage in a particular action. The Value-belief-norm theory (VBN, [12]) describes how personal norms arise. First, values will influence how one perceives consequences of behavior and awareness of problems (like climate change). Related to the energy system, this will be both environmental problems and problems with energy security. Once aware of the problems and consequences, people decide whether they are personally responsible for these problems and whether they can do something about it. When people think they are responsible they might develop personal norms that influence their behavior. For example: when people consider the importance of reducing CO2-emissions in order to limit climate change, people might decide to accept hydrogen as a fuel, even though the personal benefits of the switch of fuel might be small or even negative (e.g. when the costs are higher). The effect of normative considerations on the acceptance of hydrogen technologies has not been tested yet.

Next to these goal-frames, studies have shown that also the way the implementation of a technology is perceived and how the actors involved are perceived, influences the perceived costs, risks and benefits, and the attitude towards the technology. Three important factors in this respect are fairness, voluntariness/freedom to choose, and trust. Fairness can be distinguished into two types: procedural and distributional fairness. Procedural fairness concerns whether people find the way in which decisions were made fair. For example, decisions can be found unfair and can diminish acceptance when they were made by policy makers while citizens were not involved. Distributional fairness concerns the perceived fairness of the distribution of personal and societal costs and benefits (e.g. [13]). For example, people living close to a refuelling station might feel that a location choice is unfair to them, because they are faced with the safety risks, while others only get the benefits of the refuelling station. Both types of fairness are likely to play a stronger role when others rather than you have taken the decision for the implementation of the technology. Perceived voluntariness is found to influence the trade-off between perceived risk and perceived benefit for activities and technologies [14] and is likely to play a role in acceptance of hydrogen technologies. Trust in actors involved with the technology and actors providing information about the technology are found to influence acceptability of technologies that have risks associated with them, especially when risks are involved of which people know little about (e.g. [15, 16]). Trust has been to found to influence acceptability of hydrogen technologies in transport [11].

Finally, knowledge and familiarity are found to influence the acceptance of hydrogen. Knowledge concerns many things, like knowledge of an environmental problem (e.g. climate change and its connection to the relation between energy use, fossil fuels, and CO2-emissions) or knowledge about the way technology is currently applied. Familiarity refers to personal experience, like having been inside a hydrogen vehicle, or using a hydrogen refuelling station. Knowledge and familiarity potentially influence all previously discussed factors, depending on the type of knowledge and experience.

To conclude, we suggest that citizen and consumer acceptance are influenced by a wide range of variables, as depicted in picture one. Knowledge and familiarity are not depicted in the model, because they influence all variables, but can also act as a moderator which means that they influence the strength of the relation between the variables. The causal order is based on the causal order suggested in the original theories and measured in empirical studies. This conceptual model needs to be tested for several technology acceptance issues and specifically the relative importance of each factor for hydrogen technology acceptance needs to be tested. As made clear before, the framework includes a number of factors that have never been tested for hydrogen technology acceptance, like evaluation of environmental problems, ascription of responsibility and personal norm.

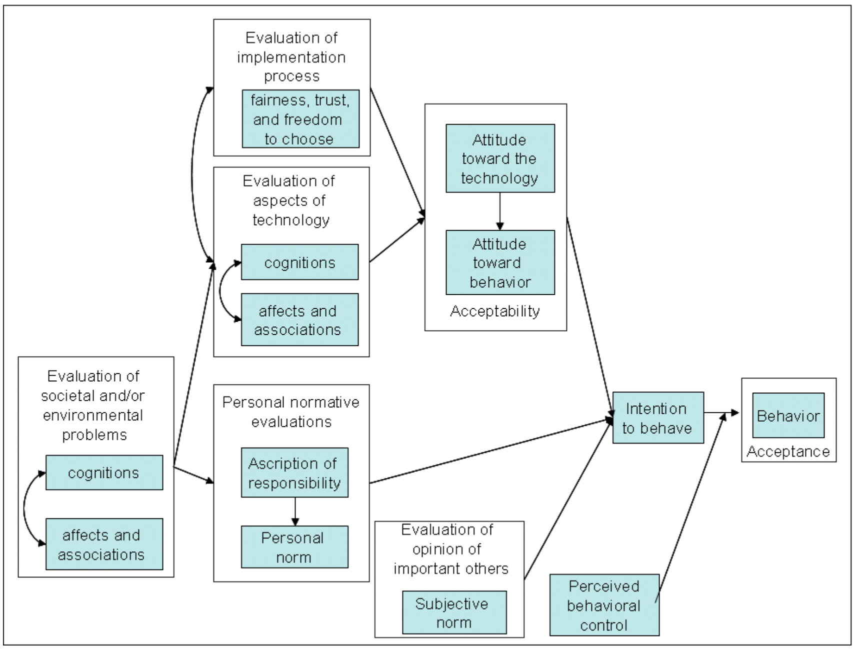



**Figure: The technology acceptance framework (TAF).**

## References

[1] EAMES, M. & MCDOWALL, W. (2007) Towards a sustainable energy future: participatory foresight and appraisal as a response to managing uncertainty and contested social values. IN FLYNN, R. & BELLABY, P. (Eds.) Risk and the public acceptance of new technologies. New York, Palgrave Macmillan.

[2] BANISTER, D. (2008) The sustainable mobility paradigm. Transport policy, 15, 73-80.

[3] O'GARRA, T., MOURATO, S., GARRITY, L., SCHMIDT, P., BEERENWINKEL, A., ALTMANN, M., HART, D., GRAESEL, C. & WHITEHOUSE, S. (2007) Is the public willing to pay for hydrogen buses? A comparative study of preferences in four cities.

[4] O'GARRA, T., MOURATO, S. & PEARSON, P. (2008) Investigating attitudes to hydrogen refuelling facilities and the social cost to local residents. Energy policy, 36, 2074-2085.

[5] HUIJTS, N. M. A., MOLIN, E. J. E., CHORUS, C. G. & VAN WEE, B. (in press) Public acceptance of hydrogen technologies in transport: A review of and reflection on empirical studies.

[6] LINDENBERG, S. & STEG, L. (2007) Normative, gain and hedonic goal frames guiding environmental behavior. Journal of social issues, 63, 117-137.

[7] AJZEN, I. (1991) The theory of planned behavior. Organizational behavior and human decision processes, 50, 179-211.

[8] MOLIN, E., AOUDEN, F. & VAN WEE, B. (2007) Car drivers' stated choices for hydrogen cars: evidence from a small-scale experiment. Transportation Research Board, 86th Annual Meeting. Washington D.C.

[9] STRACK, R. & DEUTSCH, F. (2004) Reflective and impulsive determinants of social behavior. Personality and social psychology review, 8, 220-247.

[10] HUIJTS, N. M. A., MIDDEN, C. J. H. & MEIJNDERS, A. L. (2007) Social acceptance of carbon dioxide storage. Energy Policy, 35, 2780-2789.

[11] MONTIJN-DORGELO, F. & MIDDEN, C. J. H. (2008) The role of negative associations and trust in risk perception of new hydrogen systems. Journal of risk research, 11, 659-671.

[12] STERN, P. C., DIETZ, T., ABEL, T., GUAGNANO, G. A. & KALOF, L. (1999) A value-belief-norm theory of support for social movements: the case of environmentalism. Research in human ecology, 6, 81-97.

[13] STEG, L. & SCHUITEMA, G. (2007) Behavioural responses to transport pricing: a theoretical analysis. IN GÄRLING, T. & STEG, L. (Eds.) Threats from car traffic to the quality of urban life. London, Elsevier.

[14] FISCHHOFF, B., SLOVIC, P., LICHTENSTEIN, S., READ, S. & COMBS, B. (1978) How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits. Policy sciences, 8, 127-152.

[15] SIEGRIST, M. & CVETKOVICH, G. (2000) Perception of hazards: the role of social trust and knowledge. Risk analysis, 20, 713-719.

[16] MIDDEN, C. J. H. & HUIJTS, N. M. A. (2009) The Role of Trust in the Affective Evaluation of Novel Risks: The Case of CO<sub>2</sub> Storage. Risk Analysis, 29, 743-751.

[17] BALL, M. & WIETSCHEL, M. (2009) The future of hydrogen - opportunities and challenges. International Journal of Hydrogen Energy, 34, 615-627.

# Acceptance of Hydrogen Technologies and the Role of Trust

**R. Zimmer***, Resource Protection & Landscape Ecology, Independent Institute for Environmental Concerns, Germany
**N. Hölzinger**, Spilett New Technologies GmbH, 10115, Germany

**Abstract**

It is well known in socio-economic studies, that the success of an innovation process depends not only on the technological innovation itself or the state of the economic and institutional environment, but also on the public acceptance of the innovation. Public acceptance can be an obstacle for the development and introduction of a new and innovative idea as the example of genetic engineering in agriculture shows. In respect to hydrogen technology this means, that the compilation and communication of scientific risk assessments are not sufficient to generate or enhance public acceptance. Moreover, psychological, social and cultural aspects of risk perception have to be considered when introducing new technologies. This paper focuses on trust as a central parameter of risk perception and the public acceptance of new technologies.

## 1 Acceptance

Public acceptance can be best defined as “the chance to get the explicit or implicit consensus of a group or person for specific concepts, measures, proposals or decisions” [1]. In the context of innovative technologies this includes a variety of behaviours that range from using the new technology, buying a product based on the innovative technology or simply not opposing a political decision regarding this technology. Public acceptance of hydrogen technology will be fundamental for its successful implementation. The way the public perceives hydrogen will have implications for its success or failure. One parameter influencing acceptance is the perception of risk. Other factors are general values and norms, cultural attitudes towards risk and practices for managing it, the amount of knowledge concerning a new technology, experiences with the new technology and innovations in general, prior conversations about the new technology and current incidents surrounding it.

Studies of the public acceptance of hydrogen vehicles indicate a relatively high level of acceptance. Despite low levels of knowledge regarding hydrogen technologies and fuel cells, people tend to have positive attitudes towards hydrogen, and generally accept it as a fuel. Concerns about safety risks are considered to be less important [2].

- In an analysis of Dinse [3] 150 randomly selected people in the streets of Berlin were interviewed with regard to technical, political and social implications of hydrogen vehicles. The results indicate a very high level of acceptance.

- In 2001 members of the Bayerische Eliteakademie in Munich interviewed high level executives from science, industry as well as the public sector and launched an internet survey [4]. The interviews and survey aimed at analyzing the parameters that influence the market success of hydrogen powered vehicles. Both, the interviewed executives and the survey participants showed a positive attitude towards hydrogen technologies in transport. Safety concerns were noticeable, but limited.
- Altmann and Graesel [5] analyzed the acceptance of 145 hydrogen bus passengers in Munich. The acceptance of hydrogen amongst the interviewed passengers was high. The perception of risk was low.
- In 2005 a HHICE bus was tested under cold weather conditions in Winnipeg. Interviewers used the ride to ask passengers about their perception of hydrogen technologies. The results of this study [6] indicate that the public views hydrogen as being an acceptable fuel.
- In 2003 the first hydrogen buses were introduced into the public traffic of Reykjavik (Iceland). In 2004 passengers and bus drivers were asked about their experiences. Passengers and other commuters stated that they had a positive attitude towards the new technology. The bus drivers were also had a very positive attitude towards the technology [7, 8].
- Similar positive results were found in studies conducted by Dinse [9] and VAG [10] which also indicate overall support and little opposition to hydrogen technologies and fuels.
- In the United States, a study by Hart [11] indicated that the majority of respondents supported the government decision to financially support the transition to hydrogen.
- A study by O'Garra et al. [12] revealed that the majority of people with prior knowledge supported the introduction of hydrogen vehicles. Safety concerns were low.

All of the above studies indicate a positive public attitude towards hydrogen technologies. But due to the low level of public experience with these technologies the validity of the studies for the estimation of societal acceptance seems to be rather limited. Ricci et al. [2] argue that while support for hydrogen in general may be high, support for specific applications, infrastructure or prospective large scale infrastructure build-ups could be much lower. Furthermore, it is still not yet known if the stated acceptance levels refer to hydrogen itself, or to specific hydrogen applications. It is therefore important to know which associations underlie the evaluation of hydrogen and hydrogen technologies. A systematic analysis of acceptance that includes the complete supply chain is therefore necessary to gauge the public attitude and its implications for the broad scale introduction of this technology.

## 2 Trust

The level of trust in actors or institutions, who are engaged in the development and implementation of innovations, heavily influences public acceptance as well as risk perception [13]. The source of information is highly relevant to citizens for their evaluation of

* Corresponding author, email: rene.zimmer@ufu.de

the information. This is especially true for topics that are too big or complex for individuals to understand. In these cases, people rely on the judgment of trustworthy sources [14]. Trust leads to a more emotional than rational decision process, and often results in blind trust.

Several studies reveal that the confidence people have in institutions influences their level of risk perception: The higher the confidence in an institution the lower the risk perception and vice versa [15, 16]. The „risk-survey Baden-Wurttemberg 2001" [17] for example ascertained, that the acceptance or non-acceptance of genetic engineering was determined by the confidence in the problem solution capacities of the institutions involved. Lacking confidence especially in the competence of the government to cope with a problem resulted in feelings of powerlessness that lead to a considerable change of their affective assessment and their risk-benefit evaluation.

So far, there have only been a few studies that analyze the level of public trust in the actors and institutions that are involved in the implementation and regulation of hydrogen applications in the automotive sector.

- In an opinion poll on "Public Engagement with Hydrogen Infrastructures in Transport" 1003 participants were asked to what extent they agree or disagree with the statement "Modern science can be relied on solving our environmental problems." 40 % agreed with this statement, 33 % disagreed and 25 % were neutral [18].
- A total of 12 focus groups were held in April and May of 2007 [18, 19]. Some participants of the focus groups didn't trust the government or the industry to initiate the changes necessary for a hydrogen society. They questioned the government's will to act because of vested interests and the amount of effort that was necessary. The participants didn't believe in the willingness of the government or the petrochemical industry to change the current situation as they considered them as being too reliant on the income generated from the production and taxation of fossil fuels.

In the context of the German $H_2$ mobility project – that brings nine leading companies from the automotive, petroleum and gas industry as well as an energy provider together, in order to push the nationwide build-up of hydrogen fuelling stations – it is essential to reflect these results in the German context and analyze different kinds of trust: The trust in specific institutions and the trust in the technological system as a whole.

## 3 The HyTrust Project

The German HyTrust project was launched in autumn 2009 (www.hytrust.de) and is the socio-scientific research project that accompanies the German Federal Government's "National Innovation Programme for Hydrogen and Fuel Cell Technologies". The aim of the project is to investigate

- the current state of public acceptance in hydrogen technology
- the level of public familiarity with hydrogen technologies and the public's trust in the actors who are engaged in the technological implementation
- ideas and methods for the effective and successful deployment of hydrogen technology in the mobility sector

In a first step statements and position papers of German institutions with regard to hydrogen and fuel cells have been analyzed in order to identify the general disposition towards hydrogen and fuel cell technologies in Germany. In recent years, more than 80 institutions have publicly commented on hydrogen technologies. Most position papers came from the political and industrials spheres. Most papers indicate a very positive view of hydrogen and related technologies. The main reasons that were given for support were:

- hydrogen facilitates sustainable mobility as fuel for cars
- the use of hydrogen greatly reduces pollution
- hydrogen increases the use of renewable energies in the future energy supply
- hydrogen technologies contribute to climate protection because they produce no greenhouse gases
- hydrogen based technologies strengthen the economic competitiveness of Germany
- hydrogen technologies guarantee the energy supply of the future
- hydrogen technologies are able to reduce the dependency on foreign oil and gas

In a second step interviews were conducted and focus groups were held with citizens from Berlin and Hamburg. The aim was to understand how people perceive hydrogen technologies and what future concepts citizens have for this technology. The working hypothesis being, that mental images and associations with hydrogen and hydrogen cars are a good indicator on how the technology will be framed by the public. Associations with “hydrogen” were mostly neutral and revolved around topics like chemistry, fuel cell cars and buses. One main positive association was that hydrogen enables mobility without the use of fossil fuels. There were only very few associations with the hydrogen bomb or the zeppelin disaster. Associations with “hydrogen cars” were almost completely positive. In the view of the citizens, hydrogen cars were a desirable technology for the future, because the cars are environmentally friendly, quiet and clean. The few negative associations were not linked to risks but to specific features of the car. From the citizen’s perspective hydrogen cars appeared slower, less powerful and more expensive than conventional cars.

**References**

[1] Kaiser, G.; Reese, S.; Sterr, H.; Markau, H.-J. (2004): Public perception of coastal floot defence and participation in coastal floot defence planning. Subproject 3 of COMRISK – Common strategies to reduce the risk of storm floods in coastal lowlands, Final report, p. 52.

[2] Ricci, M., Bellaby, P., Flynn, R. (2008): What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. In: International Journal of Hydrogen Energy, Volume 33, Issue 21, Pages 5868-5880

[3] Dinse, G. (1999): Wasserstofffahrzeuge und ihr Funktionsraum – Eine Analyse der technischen, politisch-rechtlichen und sozialen Dimensionen. Institut für Mobilitätsforschung

[4] Lossen, U.; Armbruster, M.; Horn, S.; Kraus, P.; Schich, K. (2003): Einflussfaktoren auf den Markterfolg von wasserstoffbetriebenen Fahrzeugen. expert verlag

[5] Altmann, M.; Graesel, C. (1998): The acceptance of hydrogen technologies. Available from: http://www.HyWeb.de/accepth2.

[6] Hickson, A.; Phillips, A.; Morales, G. (2007): Public perception related to a hydrogen hybrid internal combustion engine transit bus demonstration and hydrogen fuel. Energy Policy 35(4): 2249–55

[7] Skulason, B. (2005): ECTOS - Ecological City Transport System (EVK-CT-2000-00033) deliverable number 19, final public report. Icelandic New Energy. Reykjavik, Iceland.

[8] Maack, M. H.; Skulason, J. B. (2006): Implementing the hydrogen economy. In: Journal of Cleaner Production 14, pp 52-64

[9] Dinse, G. (2000): Akzeptanz von wasserstoffbetriebenen Fahrzeugen – Eine Studie über die Verwen-dung eines neuen und ungewohnten Kraftstoffs. Institut für Mobilitätsforschung

[10] VAG Verkehrs-Aktiengesellschaft Nürnberg (2001): Umweltfreundlicher Brennstoffzellenbus von der VAG erstmals im Linienbetrieb getestet. Befragungsergebnis der Fahrgäste liegt vor. Pressein-formation vom 22.05.2001

[11] Hart (2005): Americans' Views of Emerging Automotive Technologies. Research carried out for General Motors by Peter D Hart Associates, June.

[12] O'Garra, T.; Mourato, S.; Pearson, P. (2005): "Analyzing Awareness and Acceptability of Hydrogen Vehicles: A London Case Study," International Journal of Hydrogen Energy 30(6): 649–59.

[13] Poortinga, W.; Pidgeon, N.F. (2005): Trust in risk regulation: cause or consequence of the acceptability of GM food? Risk Analysis, 25(1), 197-207.

[14] Earle, T. C.; Cvetkovich, G. T. (1995): Social trust: Toward a cosmopolitan society. Westport, CT: Praeger.

[15] Flynn, J.; Burns, W.; Mertz, C.K.; Slovic, P. (1992): Trust as a determinant of opposition to a high-level radioactive waste respository: Analysis of a structural model, Risk Analysis, 12, pp. 417-429.

[16] Siegrist, M. (2000): The influence of trust and perception of risks and benefits on the acceptance of gene technology, Risk Analysis, 20, pp. 195-203.

[17] Zwick, M.M.; Renn, O. (2002): Wahrnehmung und Bewertung von Risiken. Ergebnisse des „Risikosurvey Baden-Württemberg 2001“, Gemeinsamer Arbeitsbericht der Akademie für Technikfolgenabschätzung und der Universität Stuttgart, Nr. 202.

[18] Bellaby, P.; Upham, P. (2007): Public Engagement with Hydrogen Infrastructures in Transport, DfT Horizon Research Programme – Contract Number PPRO 4/54/2.

[19] Ricci, M.; Flynn, R.; Bellaby, P. (2006): Public Attitudes towards Hydrogen energy: Preliminary analysis of findings from focus groups in London, Teesside and Wales, UKSHEC Social Science Working Paper No. 28, Institute for Social Cultural and Policy Research, University of Salford.

# Light Mobility Applications towards Public Education and Research

**Y. Ceviz**, **M. Eroglu**, **T. Akfidan**, **S. Altinel**, **M. S. Yazici***, UNIDO-ICHET – International Centre for Hydrogen Energy Technologies, Turkey

**Abstract**

International Center for Hydrogen Energy Technologies (ICHET) has been implementing measures to demonstrate potential benefits of the “hydrogen and fuel cell systems” in developing countries. As part of applied R&D activities, various prototype vehicles (a small tri-wheel scooter, a four-passenger cart integrated with a 2 kW fuel cell, a mobile caravan with wind, solar and fuel cell power and a forklift with the necessary fuelling options and controls) were demonstrated utilizing hydrogen as fuel. Performance analysis, sizing of the various system components and modelling will be carried out as part of applied R&D program. A long-term objective of the projects is to push for use of fuel cell powered light mobile vehicles in public places and encourage local industry to manufacturer similar vehicles and explore market potential for such use. As a benefit of this activity, public awareness on applications of renewable and fuel cell technologies will increase and viability of such systems will be demonstrated to change public perception.

## 1 Introduction

Cleaner and more efficient energy systems and transportation means will be the choice of future under scenarios for climate change and energy supply limitations. The automotive industry is already in transition from internal combustion engines to batteries and fuel cells. Electricity and hydrogen can be produced from any primary energy carrier at high efficiencies. Hydrogen and fuel cells enable almost the same personal freedom, flexibility, and ease-of-use for energy and transportation.

The International Centre for Hydrogen Energy Technologies (ICHET) act as a bridge between developed and developing countries by spanning the gap between research and development organizations, innovative enterprises and the market place in order to stimulate appropriate applications of the hydrogen energy technologies and related industrial development [1-4]. The scope is worldwide with particular emphasis on the role of developing countries. Several demonstration projects have been implemented and some are discussed below.

## 2 Mobile Hydrogen Fuelling Station

This demonstration project intends realization of mobile refuelling for hydrogen fuelled facilities while stationary item will be aside [5]. All components required for a mobile hydrogen fuelling facility will be mounted onto a truck (figure 1) as an all-in-one system to

* Corresponding author, email: syazici@unido-ichet.org

provide fuel for our demonstration vehicles and to fill up hydrogen cylinders and metal hydride canisters. Small passenger cart, three wheeled scooter and mobile house require metal hydride canisters to be filled at low pressure values, while forklift needs approximately 200 bar filling pressure on the contrary. By accomplishing this project UNIDO-ICHET will gain mobile refuelling capability. In figure 1 process flow diagram is shown. Tap water stored in a tank is sent to the DI water unit; after the process water comes out of the unit with quality of min. ~2 Megohm-cm (0.5 µS/cm), it is pumped into the proton exchange membrane (PEM) electrolyser (1.5-4 bar); via electrolysis process ultrapure water is separated into hydrogen (99.9995% purity with water vapour <5ppm, $N_2$<2 ppm, $O_2$<1 ppm impurities) and oxygen. Hydrogen stored in a buffer tank with 100 l water volume at 14 bar; and then it is compressed up to 200 bar with 1 $Nm^3$/h capacity.

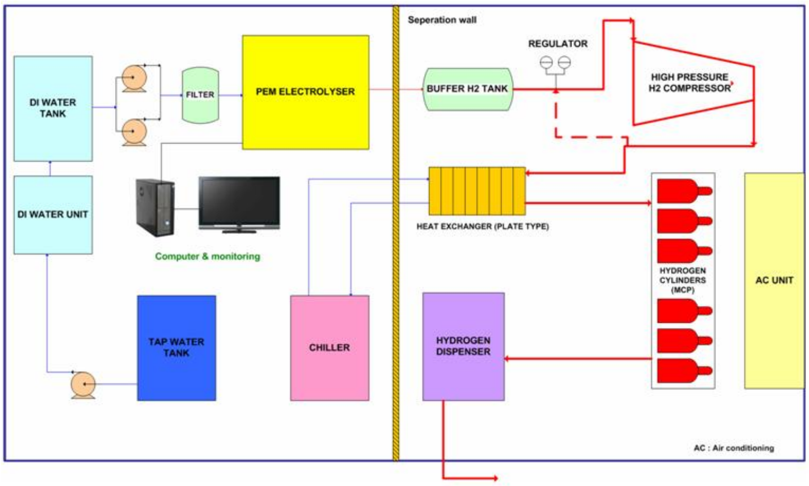




**Figure 1: Mobile hydrogen fuelling station and process diagram.**

Finally hydrogen is stored in 12x1 parallel connected steel cylinders with 50 l standard water volume at 200 bar with 100 $Nm^3$ total storage capacity. All hydrogen cylinders bundled on a common frame are connected to a single manifold with a control valve and a pressure gauge. The manifold has one inlet and 200 bar outlet to supply fuel to mobile units, 200 bar outlet to fill in the hydrogen cylinders and 15 bar outlet to fill up the metal hydride canisters.

## 3 Mobile Renewable Energy House

A photovoltaic/wind/fuel cell hybrid power system for stand-alone applications is demonstrated with a mobile house [6]. This concept shows that different renewable sources can be used simultaneously to power off-grid applications. The presented mobile house can produce sufficient power to cover the peak load. The system design was based on the results of load analysis and the study of the renewable resources available in Istanbul, Turkey. The system composed of a PV module (0.8 kW), a wind turbine (1 kW) and a PEM fuel cell (2 kW) was integrated and then mounted into the container with 3.8 kW maximum power capacity. The presented system uses PV and wind energy primarily and fuel cell energy as a secondary source for power generation. In figure 2, the energy production and demand is shown. In figure 3 and 4, block diagram and electrical diagram of the energy system are shown respectively. Load scenario assumes that 4.8 kWh energy is used per day and calculations show that in December which Istanbul has the lowest sun irradiation, energy produced from PV panels is 2.203 kWh/day and energy produced from wind turbine is 2.177 kWh/day.

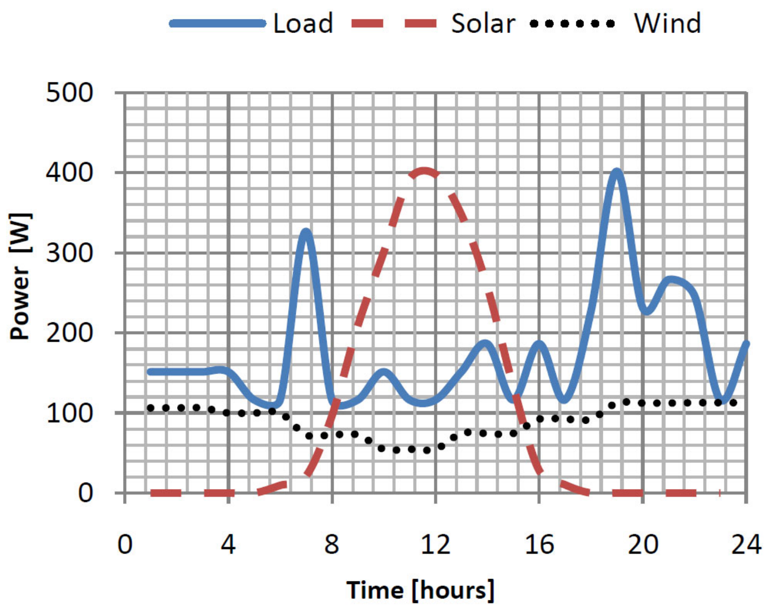



**Figure 2: Energy production and demand relevance of mobile renewable energy house.**

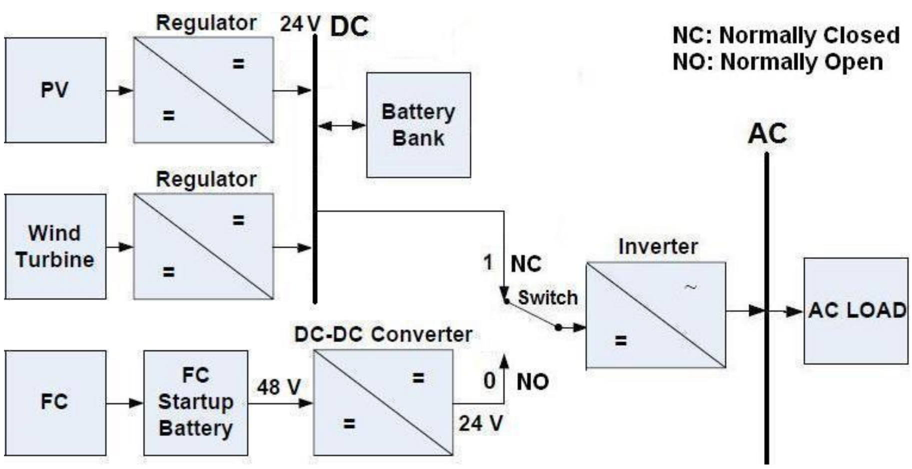



**Figure 3: Block diagram of mobile renewable energy house.**

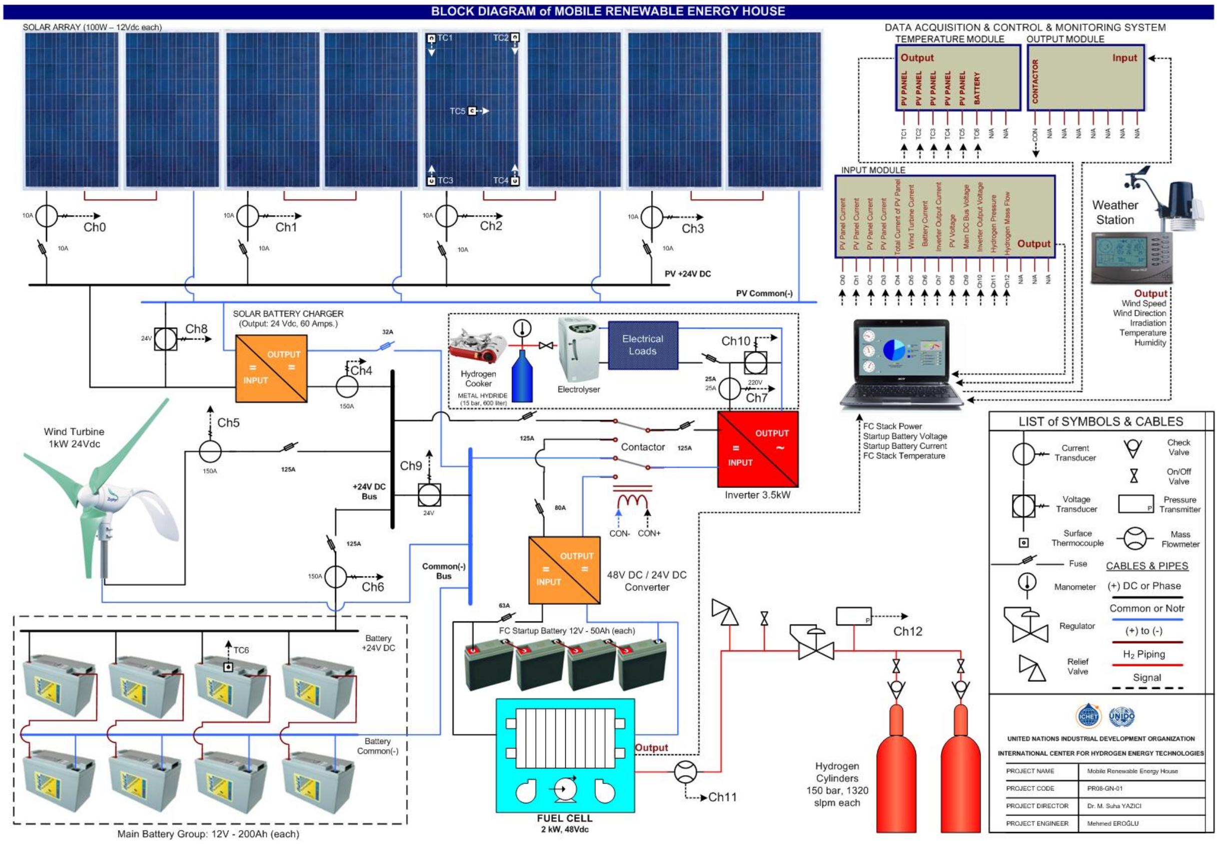



**Figure 4: Electrical diagram of mobile renewable energy house.**

Excess energy is stored in batteries and when battery state of charge drops to 50%, PEM fuel cell starts to operate. The battery bank with 19.2 kWh capacity is used in the system to supply the transient power. When the minimum battery state of charge (50%) is taken into consideration, the efficient capacity becomes 9.6 kWh which is sufficient for 1.8 days of autonomy while hydrogen cylinders with a capacity of 8.159 kWh were used at the given conditions. Moreover, the hydrogen storage is sufficient for 0.8 day of autonomy on its own when losses occur in the system; hence, the total number of autonomy is 2.6 days. Since a multi-source hybrid power system increases energy availability, mobile house can be used regardless of location, especially in remote areas and in emergency situations such as natural disasters.

## 4 Fuel Cell Passenger Cart Project

One of UNIDO-ICHET's demonstration projects is the Electrical Passenger Cart which is mainly powered by PEM fuel cell system [7]. Passenger carts, commonly used in airports and public sites to facilitate the movement of elderly and disabled people, are generally powered by battery packs. Fuel cell passenger cart prototype demonstrates that hydrogen fuel cells can be advantageously integrated into such mobile units. The Fuel Cell Passenger Cart project achieved by UNIDO-ICHET is a good model for the approach mentioned above (Figure 5). The passenger cart has a 2 kW fuel cell as main electrical power source and 1.5 kW battery group as auxiliary power unit. The hydrogen fuel cell unit generates electricity for electric motor and other electrical equipment of the cart. Batteries can be charged by plug-in or 0.36 kW solar panels. The passenger cart mostly uses electrical energy which comes from the fuel cell unit; but there are some exceptions to use the battery next to the fuel cell system. If the energy generated by fuel cell drops or motor needs power instantly (>2 kW), then the battery group supplies the electric motor next to the fuel cell system; and thus possible damage to fuel cell stack is prevented by means of battery group. The fuel cell unit is supplied by six metal hydride canisters with 3600 standard litres storage capacity of hydrogen gas (99.99% purity) at 17 bar.

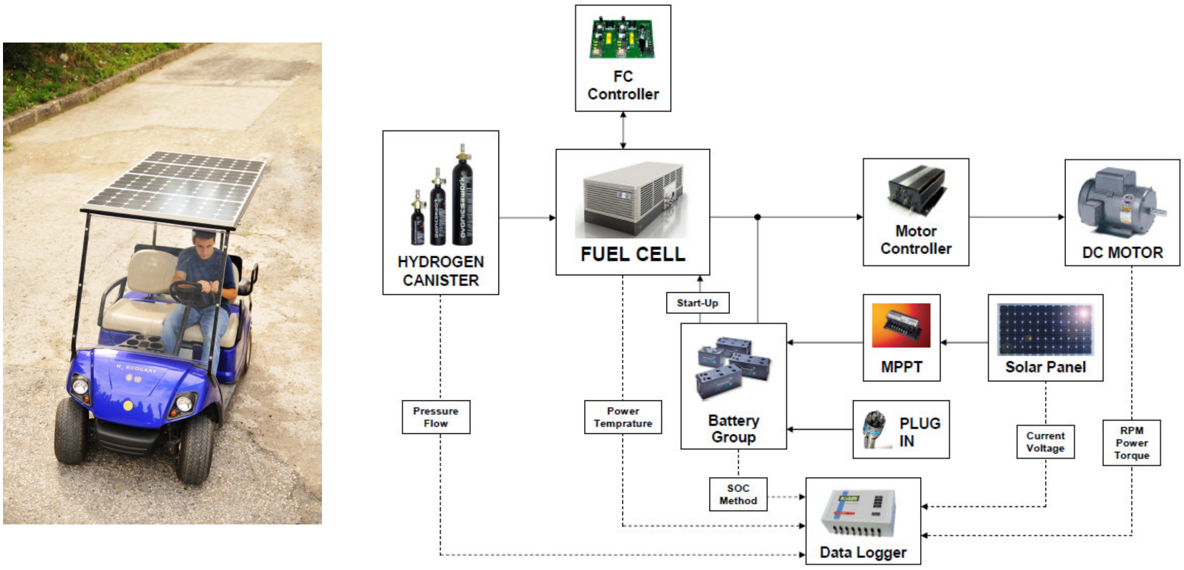



**Figure 5: Fuel cell passenger cart and system block diagram.**

Further aim of this project is to test fuel cell passenger cart on a circuit and to collect scientific data from the system. The data will be used to simulate dynamic model of the fuel cell passenger cart based on analysis programs. Following the simulation, results will be reviewed and the system optimization will be carried out for performance enhancement.

## 5 The Fuel Cell Forklift

The fuel cell forklift project intends to demonstrate the conversion of forklift powering technology from diesel engine or conventional lead-acid batteries to environmentally friendly PEM fuel cell [8]. The design and prototype phases of this project have been carried out jointly by ICHET and Cumitas, a Turkish forklift manufacturer. The hydrogen fuel cell forklift is based on the vehicle retrofitted by Cumitas and integrated by ICHET (figure 6). This 1.5 tons capacity forklift comprises an 8 kW PEM fuel cell power pack and a hydrogen storage tank. It is served by hydrogen refuelling facilities purchased from a local hydrogen distribution company, consisting of a nozzle connected to a manifold of 15 pressurized hydrogen cylinders linked in parallel. Preliminary tests have demonstrated both improved overall performance and an extended run time between fills, which together significantly increase the forklift’s productivity. Moreover, if the hydrogen is produced from a renewable energy source, the overall carbon footprint of the forklift is drastically reduced. As a unique item for technology demonstration, the hydrogen forklift is being exhibited in public events, fairs and clean energy shows throughout Istanbul as part of UNIDO-ICHET's endeavour to raise awareness and acceptance of hydrogen energy technologies.


**Figure 6: Fuel cell forklift and hydrogen filling.**

## 6 Conclusions

ICHET has several demonstration projects to promote eco-friendly hydrogen and fuel cell technologies in developing countries for them to adopt such technologies in early stage. With these initiatives, ICHET is committed to raise awareness and acceptance of hydrogen energy technologies in commercial applications. Fuel cell forklift is a relevant demonstration prototype as competitive as diesel or battery systems. Fuel cell passenger cart could be an alternative as a mobile unit for e-mobility in industrial plants or short commutes. Mobile renewable energy house is a promising prototype for system demonstration for various purposes such as disaster response unit, medical room or remote mission house. Mobile Hydrogen Fuelling Station project will give mobile refuelling capability for hydrogen vehicles and mobile units.

### Acknowledgements

Financial support of Turkish Ministry of Energy and Natural Resources is greatly acknowledged.

### References

[1] Yazici M.S., Hydrogen and Fuel Cell Activities at UNIDO-ICHET, International Journal of Hydrogen Energy, Volume 35, Issue 7, Pages 2754-2761 (2010).

[2] Yazici, M.S., Hydrogen and Fuel Cell Education Activities at UNIDO-ICHET, Extended Abstract, 17th World Hydrogen Energy Conference, WHEC-2008, June 15-19, 2008, Brisbane, Queensland, Australia.

[3] ICHET web site: www.unido-ichet.org

[4] Yazici, M.S., Hydrogen and Fuel cells: Solutions to Energy & Environmental Problems, Extended Abstract, 14th International Energy and Environment Fair & Conference, ICCI-2008, May 15-17, 2008, Yesilkoy, Istanbul, Turkey.

[5] Ceviz, Y., Villatico, F., UNIDO-ICHET Projects and Support to Hydrogen Energy Implementation in Developing Countries, Industrial Symbiosis Workshop, January 21-22, 2010, Adana, Turkey.

[6] Eroglu, M., Yazici, M.S., A Stand-Alone Mobile House using PV/Wind/Fuel Cell Hybrid Power System HYSYDAYS-2009 - 3rd World Congress of Young Scientists on Hydrogen Energy Systems, October 07-09, 2009, Turin, Italy.

[7] Hatipoglu, M., Real World Hydrogen and Fuel Cell Projects, World Future Energy Summit, January 18-21, 2010, Abu Dhabi, UAE.

[8] Lymberopoulos, N., Review of Fuel Cell and Hydrogen Strategies in Developing Countries, the European Fuel Cell Forum, June 28-July 03, 2009, Lucern, Switzerland.

# Mobile Renewable House

**M.F. Serincan**, **M. Eroglu**, **M.S. Yazici***, UNIDO-ICHET - International Centre for Hydrogen Energy Technologies Turkey

**Abstract**

International Center for Hydrogen Energy Technologies (ICHET) has implemented a demonstration project including photovoltaic/wind/fuel cell hybrid power system for a stand-alone mobile house. This concept shows that different renewable sources can be used simultaneously to power off-grid applications. The presented mobile house can produce up to 3.8 kW to provide sufficient power to cover the peak load. Photovoltaic and wind energy are used as primary sources and a fuel cell as backup power for the system. The power budgeting of the system is designed based on the local data of solar radiation and wind availability. Performance analysis, sizing of the various system components and modelling will be carried out as part of applied R&D program.

## 1 Introduction

Renewable energy technologies expected to be providing significant portion of the future energy need in the coming 20 to 50 years. However, due to the sporadic characteristics of natural resources, it has been a challenge to generate a highly reliable power with photovoltaic (PV) modules and/or wind turbines [1]. To overcome this limitation, using fuel cells as another energy source in a PV/wind/fuel cell hybrid power system may prove to be a feasible solution for stand-alone applications [2-4]. In addition, hydrogen and fuel cells enable storage and load-levelling during energy production and transportation applications. Integration of energy mix increases power availability option for highly critical applications regardless of location. This paper presents a demonstration of the use of a PV/wind/fuel cell hybrid power system to supply electricity to a mobile house. The demonstrated system shows that it is feasible to use hydrogen as an energy source with other renewable energy sources such as PV and wind energy. The hybrid power system was designed based on the data of solar radiation and wind availability in the city of Istanbul, Turkey. PV and wind energy are used as the main sources for the system and the fuel cell performs as a backup power source for the continuous generation of high quality power. The demonstration mobile house also indicates the capability of a hybrid power system which can be suitable for many other applications such as emergency vehicle, mobile clinics, mobile library and data centre.

## 2 Integrated System

A photovoltaic/wind/fuel cell hybrid power system for stand-alone applications is demonstrated with a mobile house. This concept shows that different renewable sources can be used simultaneously to power off-grid applications. The presented mobile house can produce sufficient power to cover the peak load. The system design was based on the

* Corresponding author, email: syazici@unido-ichet.org

results of load analysis and the study of the renewable resources available in Istanbul, Turkey. The system composed of a PV module (0.8 kW), a wind turbine (1 kW) and a PEM fuel cell (2 kW) was integrated and then mounted into the container with 3.8 kW maximum power capacities. The presented system uses PV and wind energy primarily and fuel cell energy as a secondary source for power generation. In figure 1, the energy production and demand is shown. Load scenario assumes that 4.8 kWh is used per day and calculations show that in December which Istanbul has the lowest sun irradiation, energy produced from PV panels is 2.203 kWh/day and energy produced from wind turbine is 2.177 kWh/day.

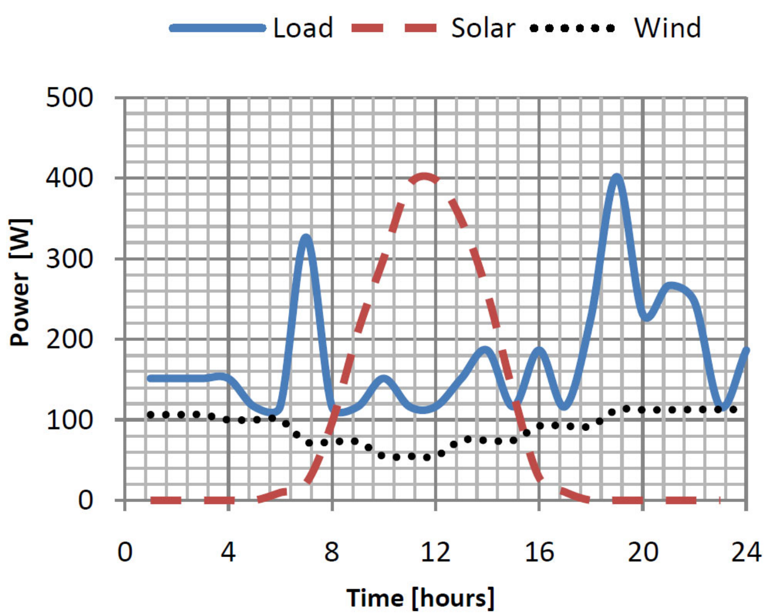



**Figure 1: Energy production and demand relevance of mobile renewable energy house.**

Excess energy is stored in batteries and when battery state of charge drops to 50%, PEM fuel cell starts to operate. The battery bank with 19.2 kWh capacity is used in the system to supply the transient power. When the minimum battery state of charge (50%) is taken into consideration, the efficient capacity becomes 9.6 kWh which is sufficient for 1.8 days of autonomy while hydrogen cylinders with a capacity of 8.2 kWh were used at the given conditions. Moreover, the hydrogen storage is sufficient for 0.8 day of autonomy on its own when losses occur in the system; hence, the total number of autonomy is 2.6 days. Since a multi-source hybrid power system increases energy availability, mobile house can be used regardless of location, especially in remote areas and in emergency situations such as natural disasters.

**System Components**: The hybrid power system of the mobile house consists of a 8x1 array of 100 W PV panels, a 1 kW wind turbine, and a 2 kW fuel cell. As shown in Figure 2, the block diagram of the system demonstrates the integrated components for power generation. In the following, each component of the system is presented and discussed.

For PV panels, Poly-Si PV modules were used to have better cost efficiency. The wind turbine, a Ventura 1000 from E-Sistem, generates 1 kW rated power with a permanent magnet synchronous generator. The wind turbine works in normal mode up to 20 m/s of wind speed, and after 20 m/s, the turbine activates a stall control system which enables electromagnetic regenerative brakes and lets the wind turbine generate power under the brake control. The turbine is installed on a foldable pole which has the height of 10 m from the ground. Although the turbines with permanent magnet synchronous generators are more expensive, they are more suitable for the mobile applications due to their compact and light structure. The Ventura 1000 is able to automatically change direction to face the predominant wind in order to generate as much power as possible.

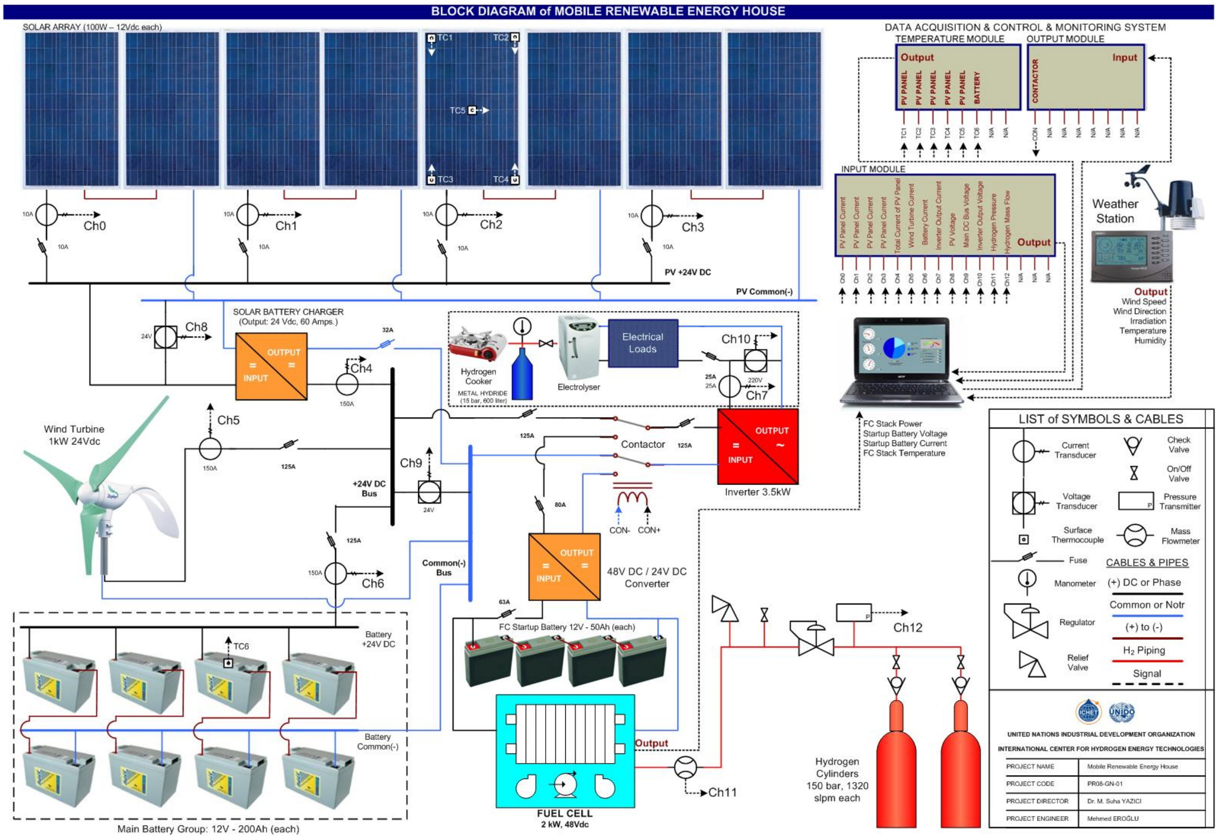



**Figure 2: Block diagram of mobile renewable energy house.**

A Jupiter B from FutureE is a PEM air-cooled fuel cell with 2 kW of rated power. Hydrogen is stored in two 10 litres tanks which are pressurized at 160 bar. PEM fuel cells with an air-cooled system are usually more suitable for mobile applications due to their low working temperatures and compact structure.

The battery bank consists of 8 gel type batteries of 200 Ah at 12 V. Sealed lead acid monoblock gelled electrolyte batteries are more tolerant of deep discharge, overcharge, and a high number of cycles. Due to their negligible gas emission, they are appropriate for residential usage. The sources and storage units are integrated on a single DC bus in order to make the system cost-effective. Having the same voltage level from the PV array and wind turbine allows both sources to be connected directly to the DC bus. Since the output of the PV module is unregulated, a 60 Amp rated Xantrex multifunction DC controller, which is capable of voltage regulation and three-stage battery charging, was used. The Ventura 1000 already has a rectifier with an internal regulator; hence, it gives an output of 24 V which is the same as the PV array. The fuel cell, which is used as backup power, has a 48 V output. Finally, a DC-DC converter was installed to convert the output of fuel cell to 24 V.

The battery bank with a capacity of 19.2 kWh is used in the system to supply the transient power. When the minimum battery state of charge (SOC) is taken into consideration, the usable capacity becomes 9.6 kWh which is the sufficient level for 2 days of autonomy. Hydrogen cylinders with a capacity of 8.2 kWh at the given conditions were used. Moreover, the hydrogen storage is sufficient for 0.9 day of autonomy when losses are taken into consideration; hence, the total number of autonomous days is 2.9 days. The startup battery group of the fuel cell prevents unnecessary switch-on when there is only a short term power demand. Since the battery group supplies the power without activating the fuel cell system, it ensures a smooth operation, allowing warm-up time in order to supply the necessary current for the future demand.

**Figure 3: The mobile house with hybrid power system.**

An automatic control system controls the energy flow and decides which energy source should supply load based on battery state of charge, hydrogen capacity, energy balance. Also control system starts and stops electrolyser when needed. For determining battery state of charge Amper-hour counting method was used with temperature and discharge, charge speed compensation. Collected data is shown to visitors on a LCD TV over an educational and simple graphical interface.

## 3 Conclusions

A demonstration of the PV/wind/fuel cell hybrid power system was presented. The hybrid power system increases power availability which is one of the key factors for many applications that need reliable power in remote locations. The mobile house, shown in Figure 3, demonstrates that hydrogen can function as an energy source with other renewable sources in order to generate highly reliable power.

The system was designed based on the results of a load analysis and a study of the renewable resources available in the city of Istanbul, Turkey. After the design, the components of the system were integrated; a PV module (800 W), a wind turbine (1 kW), and a fuel cell (2 kW) were installed to generate a maximum power of 3.8 kW. The presented system uses PV and wind energy as the primary energy sources and fuel cell energy as a secondary source for power generation.

Data collected from this study is being analyzed as an on-going project. With the collected data, a power analysis with MATLAB and LabVIEW will be conducted. For future work, the correlation between the parameters and energy production will be demonstrated to optimize the storage efficiency of the system.

## References

[1] Zahedi A. Technical analysis of an electric power system consisting of solar PV energy, wind power, and hydrogen fuel cell. Universities Power Engineering Conference AUPEC 2007:1-5.

[2] Alam MS, Gao DW. Modeling and Analysis of a Wind/PV/Fuel Cell Hybrid Power System in HOMER. Industrial Electronics and Applications. 2nd IEEE Conference on ICIEA 2007:1594-1599.

[3] Tafreshi SMM, Hakimi SM. Optimal sizing of a stand-alone hybrid power system via particle swarm optimization (PSO). Power Engineering Conference 2007: IPEC 2007: 960-965.

[4] Lagorse J, Simoes MG, Miraoui A, Costerg P. Energy cost analysis of a solar-hydrogen hybrid energy system for stand-alone applications. International Journal of Hydrogen Energy, 2nd World Congress of Young Scientists on Hydrogen Energy Systems 2008; 33(12): 2871-2879.

## SA Strategic Analyses

SA.1 Research & Development Targets and Priorities

SA.2 Life-Cycle Assessment and Economic Impact

SA.3 Socio-Economic Studies

SA.4 Education and Public Awareness

SA.5 Market Introduction

SA.7 Regional Activities

SA.8 The Zero Regio Project

# Market Introduction for Hydrogen and Fuel Cell Technologies

Marianne Haug and Hanns-Joachim Neef

**Abstract**

This article takes stock of the visions, roadmaps and the status quo of market introduction for hydrogen and fuel cell technologies. Based on innovation theory concepts, the study examines whether the framework conditions for a smooth transition form RD&D to market introduction exist. International, regional and national partnerships have started to develop supportive advocacy coalitions. Niche markets for value-driven, but limited product range like toys, portable, auxiliary and back-up applications are being established. But, market formation/ creation, development of a competitive industry and rules and regulations for the prime applications are still in their infancy. Instead, a patch work of country-, region- and product specific policies has emerged to allow "supported commercialization" beyond the demonstration stage. The study concludes that without more attention to the specifics of co-evolution of technologies and policies for each major market segment, the ongoing market introduction efforts of fuel cell and hydrogen technologies is likely to falter or create eternal niche markets.

# Overview and Status Quo of the NextHyLights Project

**Ulrich Buenger**, Ludwig-Bölkow-Systemtechnik GmbH, Germany
**Erich Ramschak**, AVL List GmbH, Austria
**Ben Madden**, Element Energy Ltd., UK
**Ingo Bunzeck**, Energy Research Centre of the Netherlands (ECN), The Netherlands

### Project partners*

| Participant organisation name | Country |
|---|---|
| AVL List GmbH | A |
| Bucher-Guyer AG | CH |
| Centro Ricerche Fiat SCPA | I |
| Daimler AG | D |
| Element Energy | UK |
| Energy Research Centre of the Netherlands | NL |
| Ludwig-Bölkow-Systemtechnik GmbH | D |
| Proton Motor Fuel Cell GmbH | D |
| Škoda Electric a.s. | CZ |
| Statoil ASA | N |
| Total Raffinage Marketing | F |
| Vattenfall Europe Business Services GmbH | D |

## 1 Project Concept and Objectives

Together with industry stakeholders, the European Commission initiated the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in 2008 to become the major instrument for coordinating and structuring the planning and implementation of hydrogen and fuel cell technologies in Europe. One of the major tasks of FCH JU is to develop a strategy for hydrogen transport applications. A first large-scale demonstration project for hydrogen powered vehicles (Lighthouse Project – H2moves Scandinavia) was therefore initiated within a first call. In parallel, this call sought for assistance to prepare the next consequent step, the planning and preparation of further large-scale demonstration projects for second-generation hydrogen vehicle fleets at further demo sites across Europe.

The Supporting Action NextHyLights works in close cooperation with and under supervision of FCH JU to develop a strategy ("Master Plan") on how to bridge the gap between today's

* Corresponding contact: Ludwig-Bölkow-Systemtechnik GmbH, Hubert Landinger, coordinator@nexthylights.eu

hydrogen demonstration projects and the start of market introduction, including the early commercialisation phase.

The concept of this proposed project is to build upon the existing knowledge from various activities including

- HFP & FCH JU (implementation plans),
- concluded EC funded strategy projects such as HyWays, Roads2HyCom and HyLights (methods, instruments and databases) and
- concluded and ongoing European key demonstration projects HyFleet:CUTE, ZERO REGIO, HYCHAIN as well as other demo projects (hardware experience).

In continuity of the former EC hydrogen and fuel cells strategy formulation, the key partners of the former FP6-funded strategy projects HyWays and HyLights assure that the results, instruments and lessons learnt from these projects can be exploited at their best.

The “Master Plan” needs to be organized in timely steps comprising milestones regarding cost and performance targets for the advancement of hydrogen and fuel cell technologies for transport.

The proposed approach to develop the “Master Plan” requires a parallel preparation of detailed work plans and roll-out plans for the vehicle segments ‘hydrogen passenger cars’, ‘hydrogen buses’ and ‘other hydrogen vehicles’. The vehicle segment specific work plans cover the time span including the large-scale demonstration projects under preparation. The roll-out plans cover the phase towards market introduction.

All plans will be checked against each other for coherence and synergies (milestones, infrastructure, and costs) and then be integrated in the overall plan.

For the sake of full transparency on “expectation management”, the project partnership decided to invite the European Regions and Municipalities Partnership on Hydrogen and Fuel Cells (HyRaMP) into the project with liaison partner status. HyRaMP was identified as the relevant body representing the European regions’ interest in hydrogen and fuel cells as their interest in individual regions is unbiased.

In case of the hydrogen bus segment a close relationship with the Hydrogen Bus Alliance (HBA) was established via the partner Element Energy which is already in charge of the Alliance’s secretariat. The work plan for the bus segment will be based on previous HBA activities such as the “Strategy for 2010 – 2015 Alliance activities on hydrogen fuelled public transit buses”. Both HBA and HyRaMP confirmed their commitment in helping to develop a FCV commercialisation roadmap via letters of support to the project.

In addition, a broader roll-out strategy has to consider a number of non-technical issues connected with the introduction of a large number of hydrogen-powered vehicles on the road as well as hydrogen production, storage and distribution. What is more, the development of a “Master Plan” also highlights and analyses the expected social and environmental impacts that a significant number of hydrogen vehicles on the roads will have. Beyond that, it is foreseen that a number of regulatory requirements have to be dealt with in order to allow for a successful large-scale introduction such as building and permission guidelines for refuelling stations, spatial planning, hydrogen metering and licensing of vehicles.

NextHyLights aims to support the planning of the second generation of hydrogen demonstration projects. In the short term, the growing number of demonstration sites will be limited. Only locations providing optimum conditions in an economic, strategic and technical way should be selected at this stage. For an objective comparison in a subsequent selection of sites it is necessary to apply an appropriate tool. The project HyLights developed such a tool called the "Regions Eligibility Assessment Tool" to be used by FCH JU in order to identify regions / municipalities which are suitable hydrogen cluster regions. In particular the tool allows assessing to which extent a region already inherits features that could allow a further sustainable ramp-up of planned demonstration projects. As the current version of the tool has been tailored for early demonstration projects, it needs to be modified to be also applied for later stage demonstration projects. NextHyLights will advertise the tool to FCH JU and promote its application.

It is foreseen to interconnect the early model regions via hydrogen corridors at a later stage and add further hydrogen clusters to eventually establish a widespread and interlinked hydrogen infrastructure.

NextHyLights has been called for to contribute to the FCH JU activities in the preparation of the next calls and is prepared to react flexibly on its requirements. It uses the Multi Annual Implementation Plan (MAIP) as the basis and adds to it in detail to develop the next Annual Implementation Plans (AIPs) taking the ambitions and opportunities of all stakeholders into account.

### Overall Strategy and General Description

The project NextHyLights deals with all vehicle segments for which near- or medium-term market introduction is to be expected. As the various segments require different strategy frameworks, the project layout foresees a specific work package for each vehicle segment as shown in Figure 1.

Each of these work packages also deals with specific hydrogen infrastructure requirements for the vehicle segment. The identification of synergies regarding the hydrogen infrastructure is the main task of WP 5 "Exploring synergies of hydrogen infrastructure".

In WP 6 social and environmental impacts of the introduction of hydrogen powered vehicles and of the required infrastructure will be assessed at an integral level for all vehicles. Regulatory requirements will also be considered.

A key element of the project is the development of the assessment framework for additional hydrogen demo sites. The results of this WP 7 effort can be directly used for drafting the next FCH JU calls.

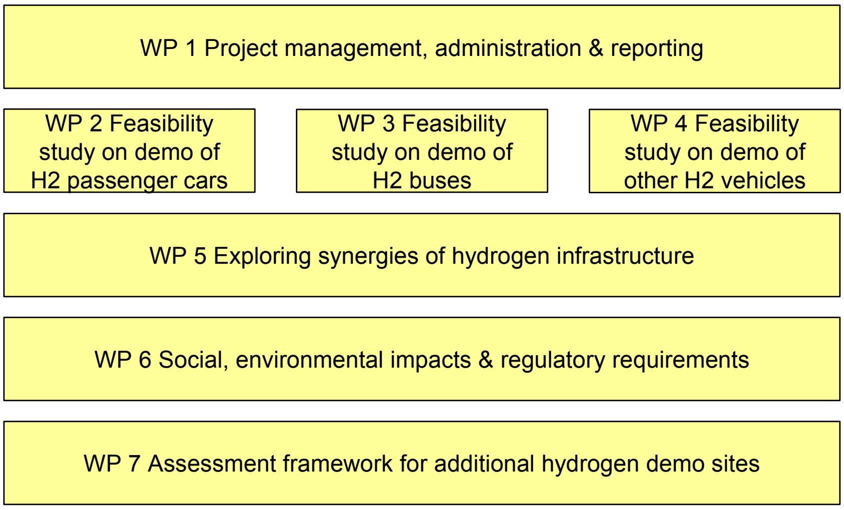



**Figure 1: Work package structure of NextHyLights.**

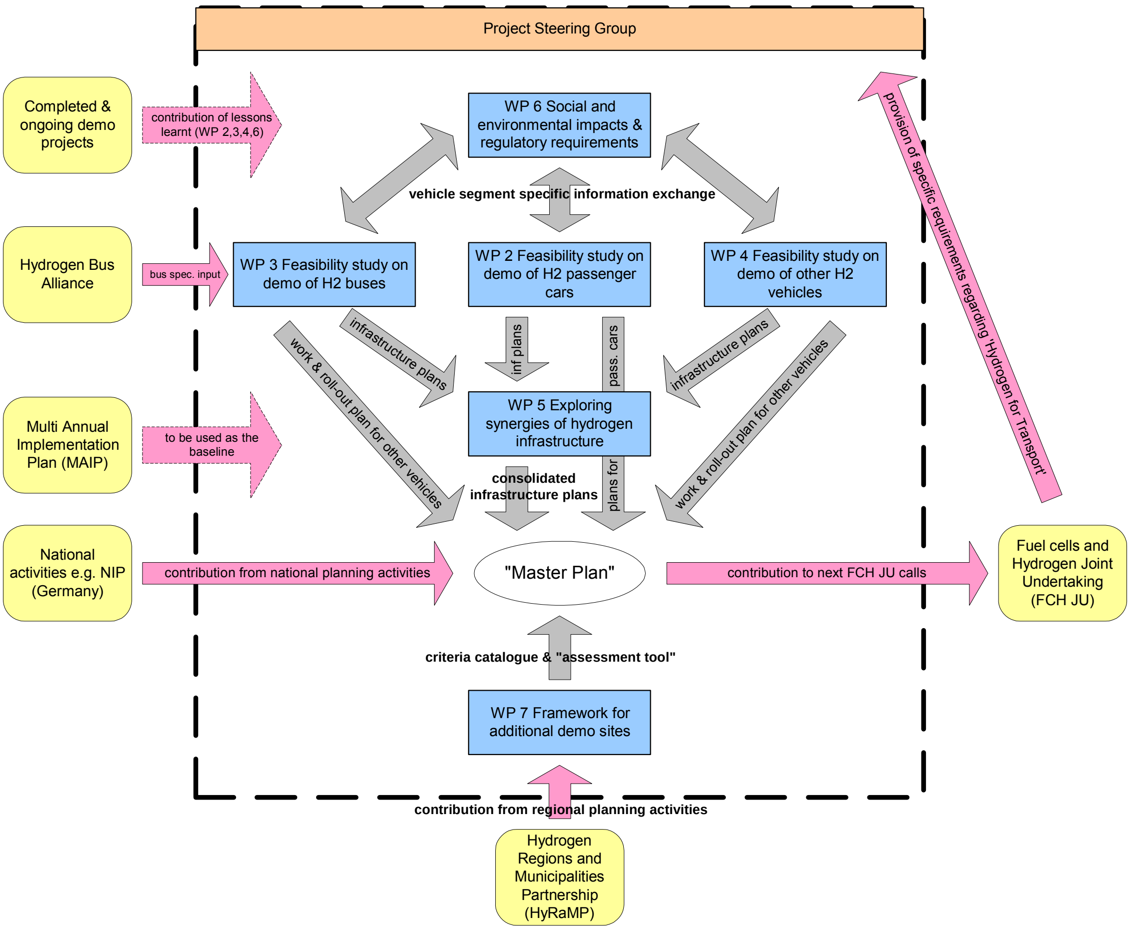



**Figure 2: Interfaces between work packages and to the FCH-JU environment.**

## 2 Strategic Impact

Feasibility studies are performed for three different hydrogen vehicle segments – for passenger cars, buses and other vehicles. This differentiation has been chosen as the requirements for each of these segments differ significantly, not only regarding the required infrastructure but also in the required concept of the demo projects and the expected timeline towards market introduction.

These feasibility studies result in work plans to propose the configuration of large-scale demonstration projects for second generation vehicle fleets. The project takes key factors such as performance of the vehicles (improved durability, robustness, reliability, efficiency, etc.) and of the infrastructure (daily usage, subsequent refuelling, etc.) into account. Furthermore, roll-out plans for each vehicle segment which are based on the work plans provide advice on the path from large scale demonstration projects to market introduction.

A separate work package assesses the environmental as well as the social impacts resulting from the implementation of the above mentioned work and roll-out plans. Regarding environmental impacts the reduction of noise and local pollutants in city centres as well as the impact on GHG emissions are assessed, taking into account a large-scale demonstration setting as well as the further up-scaling of the whole system into an (early) commercialization environment. Regarding social impacts, the project evaluates potential obstacles from the societal perspective and develops strategies which foster a positive attitude within the public towards large-scale hydrogen demonstration projects. Issues are how acceptance for hydrogen demonstration projects can be actively pursued in the public, how a positive image of the projects can be created and how NIMBY (not in my backyard) effects can be avoided (important especially for hydrogen refuelling stations). This work package assesses the importance of stakeholder involvement by applying the EESTEM tool, one of the main results of the FP6 project Create Acceptance. This tool could be used to improve the engagement of stakeholders in multi-stakeholder environments.

Currently the number of demonstration projects on hydrogen for transport in Europe is limited. The most important ones are HyFLEET:CUTE, ZERO REGIO, HyCHAIN, ZEMSHIPS, CEP and HyNor, some of which have already been terminated or will end in the near future. At the moment, the first demonstration project of the FCH JU (H2moves Scandinavia) which has been started recently is the only new large-scale demonstration project. For this reason a framework to establish a cluster of European demonstration projects organically evolving from and building on the existing projects needs to be developed. NextHyLights's ambition is to develop this framework by providing adequate instruments and tools as outlined above.

NextHyLights will provide a criteria catalogue and a framework for the selection of appropriate candidate regions / municipalities to become cluster regions / municipalities for a future large-scale hydrogen demonstration project. The criteria catalogue will cover a number of technical and socio-economic indicators (e.g. available infrastructure, regulatory conditions, governmental support, potential renewable hydrogen production, availability of by-product hydrogen, preparedness for interconnection with other hydrogen cluster regions / municipalities, etc.). In particular, the assessment framework in particular addresses the potential for further growth around a cluster region / municipality. This includes the investigation of connectivity with other cluster regions / municipalities, the profiles of local stakeholders that could become early market adopters (e.g. continuation of HyLights gaps analysis) and the potential to increase the numbers of vehicles applied (10 → 100 →1,000 → 10,000 → 100,000).

NextHyLights also performs an assessment of the regulatory requirements for the hydrogen clusters in EU regions / municipalities. In some countries (e.g. France) institutional barriers for the operation of hydrogen powered vehicles on public roads, the installation and operation of hydrogen refuelling stations, or the distribution of hydrogen fuel may be serious hurdles regarding the smooth implementation of large-scale hydrogen demonstration projects. In order to attain reliable information, permitting guidelines and previous demonstration projects are consulted and the outcome is reflected in the near-term planning activities which potentially have to take place by spatial planning. Furthermore, the planning activities will take into account national, regional or local policy incentives for hydrogen vehicles and / or infrastructure which support the implementation of these technologies. Also, stakeholders' experiences from previous demonstration or planning projects are taken into account (e.g. HyLights, HyApproval, etc.).

Within the course of the HyLights project the European initiative on hydrogen for transport - H2moves.eu was created. In the context of H2moves.eu a close liaison with all relevant demonstration projects on hydrogen for transport in Europe has been established. The continuity of the same coordinator is an asset of NextHyLights helping to rapidly link with the existing demo project network.

Furthermore, the NextHyLights consortium is prepared to contribute to the preparation of the next FCH JU calls regarding demonstration projects on hydrogen for transport. As the consortium comprises many of the major industrial players in this field and as it established a liaison to the European Regions and Municipalities Partnership for Hydrogen and Fuel Cells (HyRaMP), the contributions provided by the project may be well balanced, receive serious industrial backing and cover a sound expectation management.

As all of the work is performed in close collaboration with the FCH JU bodies, especially with the JTI Governing Board and the JTI Programme Office, the NextHyLights partnership can react flexibly on FCH JU requirements and therefore can be seen as its prolonged workbench.

## 3 Integration of National and International Activities

The consideration and integration of national activities is of great importance for the NextHyLights project since close coordination between national strategies for the implementation of hydrogen for transport and the EU-wide approach can save resources and optimise the formation of cluster regions and hydrogen corridors. NextHyLights therefore liaises with national programmes such as the German NIP programme,

As long as national and regional demonstration projects are prepared to share information with other projects and programmes, NextHyLights welcomes the opportunity to learn from these demonstration projects and / or to perform an assessment in order to broaden its data base. As liaisons with national projects such as CEP or HyNor have already been established by HyLights these liaisons are further exploited for collecting valuable inputs for the NextHyLights project.

Internationally, NextHyLights collaborates with the International Partnership for the Hydrogen Economy (IPHE). Furthermore, NextHyLights is prepared to review and cross-check plans and activities of IPHE in order to ensure that strategic plans are aligned, especially with the "Master Plan".

**Acknowledgement**

The project partners would like to thank the EC for establishing the New Energy World JTI framework and for supporting this activity.

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under FCH-JU-2008-1 Grant Agreement N°245133.

# Hydrogen at Wastewater Treatment Plants – Optimal Conditions for the Start-Up of a New System

**Markus Schröder**[*], **Friedrich-Wilhelm Bolle**, **Sylvia Gredigk-Hoffmann**,
TUTTAHS & MEYER Ingenieurgesellschaft mbH, Germany
**Henry Riße**, FiW Forschungsinstitut für Wasser- und Abfallwirtschaft an der RWTH Aachen e.V., Germany

## 1 Introduction

In the context of the present discussions on sustainable energy supply concepts hydrogen is often one of favoured solutions. Today however, hydrogen production is globally still based on fossil fuels. Hydrogen is generated for instance as a by-product of industrial processes (e. g. chlorine-electrolysis) or when reforming natural gas. The expected advantages as to sustainability can only be granted, if already the hydrogen generation process complies with the sustainability-principles – using regenerative energy sources.

Within this scope wastewater treatment plants (WWTP) offer two possibilities:

1. Hydrogen & oxygen generated from water with regeneratively operated electrolysis
2. Hydrogen generated from digester gas through gas purification (cleansing, reformation, reformate-conditioning)

Bearing in mind additionally that wastewater treatment plants, with an energy demand comparable to a large industrial unit, are still majorly dependent on the public power network the combination of both processes can provide for a grid-independent regenerative energy supply. The electricity surplus, e. g. from wind power, can be applied to generate hydrogen via electrolysis. For this purpose WWTP are predestinated, as the "waste-product" of the electrolysis, pure $O_2$ resp. $O_3$, can be beneficially applied to the aerobic wastewater treatment process. During periods of low feed-in from regenerative sources buffered HY-energy can be, e. g. electricified in fuel cells and the surplus in turn be fed into the power grid. The hereby generated "waste-product" heat can be efficiently applied to the treatment process, too.

Furthermore, hydrogen-based WWTP could be linked in a network of decentralised power stations ("virtual power plant") improving their resources-management in comparison to the isolated, unlinked operation.

Aside these aspects WWTP bear a so-called "location-advantage" (optimal link-up to transport, supply- and disposal-infrastructures, expert personnel, permanently supervised operation, etc.) making WWTP favourable as future hydrogen generation sites for hydrogen-based energy concepts.

[*] Corresponding author, email: m.schroeder@tum-aachen.de

## 2 Hydrogen & Oxygen Gained from Water with Regenerative Electrolysis

One possibility to gain hydrogen is by electrolysing water. Electrolysis becomes important whenever non-storable regenerative energy is to be provided for continuously. During strong-wind periods, for example, surplus energy from wind power plants can be stored as hydrogen and applied as energy-source during weak-wind times ("base-load efficiency of regenerative energy"). The special advantage of WWTP here is the possibility of applying the pure oxygen, generated as by-product during electrolysis, to the wastewater treatment process. This in turn leads to a considerable reduction or even total substitution of the main energy demand of the WWTP, the aeration of the biological treatment stage (approx. 3 TWh/a energy demand on German WWTP). These circumstances will always result in a location-advantage for WWTP with regard to electrolysed hydrogen respectively pure-oxygen generation.

An additional advantage for new constructions or extensions of existing WWTP not to be neglected is the reduction of necessary volume and surface area for the biological wastewater treatment stage when applying pure oxygen to the treatment process.

With the present discussions of advanced requirements concerning wastewater treatment this location-advantage will most probably gain importance. The advanced requirements comprise in particular, the oxidisation of very slowly degradable substances and organic trace elements such as pharmaceutical residues and the disinfection of WWTP-effluent. In this case ozone ($O_3$) would be applied, which could be generated from the by-product of the electrolysis – pure oxygen.

## 3 Hydrogen from Digester and Bio Gas

Regenerative hydrogen can be recovered from methane-consisting digester gas when applying cleansing and further conditioning processes. The choice of the purification processes is strongly dependent on the further application of the resulting hydrogen.

As an intermediate product of hydrogen generation bio natural gas, resp. bio methane can be generated. Today, the process of conditioning digester gas to natural gas quality and its feed-in to the public gas grid or its application as fuel for vehicles is of more importance outside Germany, especially in the Netherlands, Sweden and Switzerland. Historically however, this application was well distributed in Germany, too. In the 1950's for example, conditioning stages were in operation at the WWTP Mönchengladbach-Neuwerk (pressure water cleansing) and Stuttgart-Mühlhausen (chemical-physical cleansing with mono ethanolamine-treatment).

The advanced treatment technologies for the hydrogen generation from digester resp. bio natural gas or methane gas are highly innovative and of model character still. The purification of digester gas to hydrogen can be implemented through reformation and following a reformate-treatment (steam-reformation, partial oxidisation, partial oxidisation with catalyst or autothermic reformation). The reformate-treatment is dependent on the projected hydrogen-application. Applying pure hydrogen in PEM fuel cells for instance, requires a CO- and $CO_2$-free gas. Possible treatment steps could then be shift-reaction resp. exothermic conversion, selective oxidisation or pressure swing adsorption. Extensive large-scale experiences with digester or bio gas as starting product are yet to be made.

The overall treatment system from digester gas to pure hydrogen with the intermediate product bio methane was firstly implemented on a large-scale base at the WWTP Bottrop of the Emschergenossenschaft (project name: EuWaK). Presently this plant is in the operation and optimisation stage.

Roughly approximately 10 $m_N^3$ gaseous hydrogen can be generated per treated population equivalent (PT). The digester gas and in turn the hydrogen yield can be increased up to 30 % with an additional sludge-disintegration stage – sludge-cell disruption releasing additional supporting enzymes.

## 4 Further Options

WWTP also offer further hydrogen production possibilities. The direct production of $H_2$ from sewage sludge and other biogenic residues through microbiological conversion or thermal treatment, such as gasification or hydrothermal $H_2$-generation can be implemented. Today however, microbiological processes with photolysis through algae, cyano or purple bacteria still seam inefficient due to low production rates. Higher production rates and a more common process realisation might possibly be the two-staged „Dark Fermentation." This process combines an anaerobic microbiological hydrolysis with $H_2$-generation and a downstream methane stage for the transformation of the substrate leftovers. The microbiological $H_2$-generation could be combined with the already well-established sludge digestion. However, the reviewed processes of microbiological $H_2$-generation are still in laboratory and early pilot plant stages. The research-demand is thus very high, not only for the fundamental process management (substrate-adaption, microbiology, process-stability) but also with regard to the scale-up.

Aside the application of hydrogen, natural gas and bio gas the application of methanol in Direct-Methanol-Fuell-Cells (DMFC) is possible, too. Then, the reformer is directly integrated in the fuel cell. Comparing the handling of methanol to that of hydrogen, this technology becomes of more interest. One approach here is methanol synthesis, the combination of digester gas with hydrogen generated through electrolysis and $CO_2$-gas, e. g. from the exhaust gas from combustion engines.

## 5 Prospects

Today, producing hydrogen and pure oxygen through electrolysis as well as generating hydrogen from bio gas at WWTP has already been implemented successfully in the context of pilot plants and research and demonstration projects. New approaches are now made towards the methanol generation at WWTP – here too offering numerous outstanding advantages.

The first advantage is that methanol has a much higher energy storage density compared to gaseous fuels – especially hydrogen. The second advantage is that the usage of methanol is possible with the existing infrastructure designed for the application of liquid fuels. The methanol synthesis also bears the possibility to fix technical waste $CO_2$ and create a real sink for $CO_2$.

These regenerative energy sources all supply for a wide spread of FC-applications reaching from mobile to stationary, large-scale to small-scale systems.

WWTP have general location-advantages for the implementation of these systems other locations do not have or at least not in such a scope:

- Wide-spread net (e. g. in Germany more than 1,000 of the total 10,000 WWTP have a suitable location);
- Existing infrastructure (electricity, gas, water);
- Technically trained expert personnel;
- High level of operational security and monitoring;
- Own vehicle-pool as consumer;
- Optimal location near towns and supra-regional integration in road network.

With operators of WWTP and hydrogen-experts recognising and applying these potentials, WWTP can essentially support the positive development of a hydrogen-infrastructure. To start-off with a special focus must be set on niche solutions with pilot-character for the entire infrastructural scope, short-term implementation periods and thus an economic advantage over single-solutions.

All these potentials for the configuration of the future public energy-supply system are combined at the location of a WWTP, as all infrastructural compounds find a clustered implementation here.

# Hydrogen Rickshaws Fleet Demonstration in New Delhi

**F. Villatico**, UNIDO-ICHET United Nations Industrial Development Organisation – International Center for Hydrogen Energy Technologies, Istanbul, Turkey
**L. M. Das**, IIT Indian Institute of Technology, New Delhi, India
**M. Abraham**, Mahindra&Mahindra, Satpur Nashik, India
**Ian Willianson**, Air Products, Allentown PA, USA

## 1 Introduction

The project proposal for "Development and demonstration of hydrogen fuelled three wheeler vehicles in New Delhi" is very relevant in the context of the emerging energy-environment scenario in India. Most of the recent steps to bring down the pollution level in the cities of India have been very effective. The route of alternative gaseous fuel utilization such as Compressed Natural Gas (CNG) has shown remarkable results. The project activities aim at introducing the most environmentally friendly gaseous fuel, hydrogen, so as to drastically reduce the high levels of pollutants present in the ambient air. Furthermore hydrogen operated three wheelers will be able to send the signal in favour of hydrogen as the most environmentally friendly alternative transportation fuel. The three-wheelers have been chosen for this project as they represent a common mode of affordable public transport in India. It is proposed to operate a fleet of 15 three-wheelers (3W) vehicles powered by hydrogen in the site of New Delhi.

The project consortium is composed by:

1. UNIDO-ICHET who is providing funding to the project;
2. Indian Institute of Technology (IIT) of Delhi, the technical coordinator and expert in the engines conversion to hydrogen fuel;
3. Mahindra and Mahindra (M&M) who is supplying the vehicles fleet;
4. Air Products who is supplying the refilling facility;
5. UNIDO regional office in India, who is facilitating the on field operation.

Demonstration of developed concept on full hydrogen operation of Spark Ignition (SI) engine in small vehicles (three-wheelers) is the most innovative approach of the present proposal. The concept has already been developed and it is proposed to employ a fleet of such vehicles to study performance and exhaust emission characteristics of the vehicle within an exhibition area (Pragati Maidan) in New Delhi, India. Pragati Maidan offers 62,000 sq.m of covered exhibition space in sixteen conference and convention halls for hosting workshops, symposia, seminars and trade meetings. ITPO (India Trade Promotion Organisation) manages the exhibition complex.

Demonstrating hydrogen technology to face vehicle emission is one of the key aspects of this project. Such a study would bring out glaringly the ample benefits of hydrogen operation over that of conventional three wheelers.

Obnoxious pollutants such as carbon monoxide, carbon oxide, un-burnt hydrocarbons, oxides of sulphur, particulates will be absent in the exhaust of the vehicle. Then, by operating the fleet in an internationally reputed tourist spot in New Delhi, the project will send a positive signal to other South Asian countries where three wheelers are also used for public transportation. A hydrogen refuelling infrastructure will be set up on site.

Pragati Maidan is India's only world-class exhibition complex.

## 2 Technical Description of 3W Conversion

M&M and IIT jointly developed a hydrogen engine system and M&M later developed a commercially viable three wheeler called as “HY Alfa”. This vehicle is the first of its kind in India and abroad running with compressed hydrogen gas.

The existing CNG operated three wheeler was modified for hydrogen operation and extensive experiments have been conducted to optimize the engine. Based on IIT recommendations, M&M had developed a hydrogen operated three wheeler for passenger and cargo version use. However these vehicles have been re-optimized to meet the performance and emission norms of Bharat Stage IV (BS-IV) Indian emission standard (which corresponds to EURO 4 norm of EU). This process includes

1. Initial Engine Testing
2. Recalibration of ECU and fuel injection system
3. Optimization of the engine for performance and emission
4. Integration of hydrogen storage system, fuel supply system and safety system in the vehicle for field demonstration.

The vehicle is designed ideally to suit city driving with zero carbon based emission. The NOx emission meets BS-IV target thanks to ECU controlled fuel injection and ignition.

**Table 1: Engine Specification & Performance.**

| Engine Specification & Performance | |
|---|---|
| **Type** | **4 stroke** |
| Bore * Stroke | 86*68 |
| No Cylinders | One |
| Cooling Method | Air Cooled |
| Max Power | 4.8kW @ 3600 RPM |
| Max Torque | 13 Nm @ 2000-2200 RPM |
| Capacity of the engine | 395 CC |
| Pay load | 3+1 |
| Gross vehicle weight | 850 Kg |
| Fuel consumption | 95 Km /Kg |

The Engine Control Module (ECM) is a programmable microcontroller based device. It takes signals from different sensors (position and MAP Sensor) and decides the injection and ignition timing and duration of injection at different operating conditions.

ECM is programmed with open loop control strategy with inbuilt map control for A/F ratio range. This is a patented module specific to the Hydrogen operated 3-Wheeler Hy Alfa. The

ECU is also protected to adopt close loop control strategy which needs remapping and optimization.

The following sensors are used to operate the engine on the open loop control strategy

1. Engine Speed or Crank Position sensor: Crank position sensor is mounted on the flywheel to measure engine speed as well as the crank position. It is an inductive type pick up sensor.
2. Phase sensor: It is mounted on Cam Shaft of the engine and works on Hall Effect principle. Whenever lob of camshaft comes in front of the sensor a signal is generated. Based on this signal piston position is decided through the position of the generated signal. In this way start of injection can be varied based on this signal.
3. Temperature and Manifold Pressure Sensor (TMAP): This sensor measures absolute pressure in the intake of the engine which is correlated to measure load of the engine. We know that when there is increase in load on engine, manifold vacuum decreases and vice versa. MAP sensor senses this vacuum.

The injector is specially made for Hydrogen fuel and it is produced from a specialised supplier. The flow rate is chosen as per the engine requirement. The injector quantity is controlled by modulating the pulse width which is controlled by the ECU map.

**Table 2: Comparison between HyAlfa Load Carrier and CNG Alfa passenger vehicle speed.**

| | **3 person sitting** | **Loaded** | **Unloaded** |
|---|---|---|---|
| | HyAlfa Load Carrier | CNG Alfa Passenger | |
| **top speed(kmph)** | 36 | 52 | 57 |

**Table 3: Comparison between CNG and hydrogen engines data.**

| **CNG** | | | **Hydrogen** | | |
|---|---|---|---|---|---|
| **Engine Speed** | **Torque** | **Power** | **Engine Speed** | **Torque** | **Power** |
| RPM | Nm | kW | RPM | Nm | kW |
| 1200 | | | | 12.11 | 1.56 |
| 1600 | 18.6 | 3.1 | 1200 | 13.05 | 2.18 |
| 1800 | 18.5 | 3.5 | 1600 | | |
| 2000 | 18.2 | 3.8 | 2000 | 13 | 2.73 |
| 2200 | 18.4 | 4.3 | 2400 | | |
| 2400 | 18.6 | 4.7 | | 12.41 | 3.04 |

The improvement of the existing system is oriented towards the adoption of higher compression ratio to improve thermal efficiency. The above comparison shows a power loss around 30% for hydrogen operated vehicle with a compression ratio of 8.5. To increase the power the compression ratio of the engine has to be also increased. Hydrogen is having higher auto-ignition temperature, so compression ratio can be increased without any abnormal combustion.

## 3 Hydrogen Storage and Supply System

Concerning safety issues appropriate hydrogen sensors, valves and arrestors are mounted to prevent the storage system form detonation and flame propagation risks.

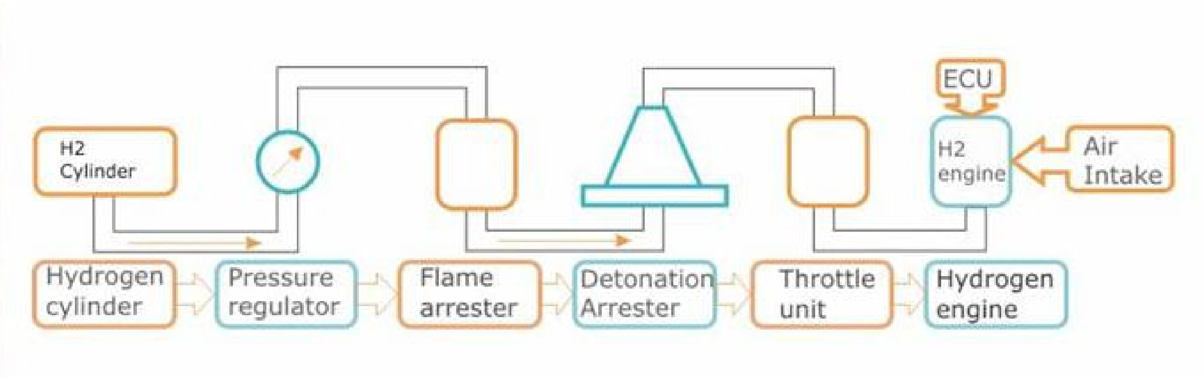



**Figure 1: Hydrogen storage and safety system.**

Conversion system is a manifold injection system which injects metered quantity of gas inside the manifold. Backfire is very prominent in hydrogen engine because it requires very small energy to ignite. In order to avoid back fire timed manifold type of injection has been chosen.

For safety purposes one hydrogen sensor is also integrated into the conversion system. A sensor is installed in the hydrogen cylinder compartment. As soon as the detector detects the hydrogen leakage ECM cut the fuel supply to the injector by relieving the gas solenoid plunger and blowing an alarm to the driver cabinet.

In case of backfire there is a chance for flame front to propagate through injector to cylinder. To quench the flame before it reaches the cylinder a flame arrestor has been installed between the cylinder and injector. Maximum working pressure of flame arrestor is 9 bar. It quenches the flame as well as acts as a NRV (Non Return Valve) device. This spring loaded NRV prevents slow or sudden reverse flow forming an explosive mixture in the gas supply. In addition to this, a manual shut off valve is utilised (Quarter Turn Valve). In case of any problem with the solenoid or regulator manually the fuel supply can be switched to a shut off position by manual shut off valve.

## 4 Field Testing and Evaluation

The vehicles would run for approximately 40 km per day. However the usage envisaged for the passenger vehicles is up to 8 hours a day and up to 10 hours for the goods vehicles. During the on field testing all the main parameters of the vehicles will be monitored in order to carry out a specific energy and environmental analysis of the hydrogen fleet based on real data. A CAN BUS communication protocol will be set up in order to download onboard data and post-process them. Furthermore the on field data will also enable to deepen design process, running costs and thus investment costs.

## 5 Conclusions and Future Developments

India has demonstrated to be one of the main candidates to take part in the hydrogen drive. First of all it is the only developing country featuring a Ministry of New and Renewable Energy (MNRE). Then a set of important initiatives have been undertaken:

- In 2003 a National Hydrogen Energy Board has been set up under MNRE;
- in 2007 a Hydrogen Roadmap has been prepared;
- green Initiative for Future Transport (GIFT), one million hydrogen fueled vehicles on the road by 2020;
- Green Initiative for Power Generation (GIP): 1000 MW of H2 powered ICEs, gas turbines and high temp fuel cells (FC).

Within this context a recent order for 40,000 FC-based UPS units for telecomunication has been placed. Due to the country size these initiatives carry a high potential to generate a real market and make India a hydrogen worldwide leader. Only in Delhi more than 50,000 CNG three-wheelers are circulating as Diesel fuel is banned from Delhi's area. Starting from the first of April 2010 all two and three-wheelers in India have to comply with BS III (EURO 3) emission norm whose emission limits in g/km are given in the following table.

**Table 4: EURO 3 and EURO 4 emission standards.**

| Norm | CO | THC | NOx | HC+NOx | PM |
|---|---|---|---|---|---|
| EURO 3 Diesel | 0.64 | | 0.50 | 0.56 | 0.05 |
| EURO3 gasoline | 2.3 | 0.2 | 0.15 | - | - |
| EURO 4 | 0.5 | | 0.25 | 0.3 | 0.025 |
| EURO4 gasoline | 1.0 | 0.1 | 0.08 | | - |

The environmental benefits related to the introduction of hydrogen fleets in comparison to conventional vehicles are then significant as regards the carbon based emission. With special reference to CO2 emissions the reduction gained in the passage from gasoline to CNG three-wheelers was around 12% (from 105 to 94 g/km). Hydrogen introduction will lead to completely eliminate this greenhouse gas production. Also NOx, thanks to the upgraded ECU, will be kept within EURO 4 limits (see table 4). Fleet applications suit very well hydrogen as a fuel in order to bypass the lack of refuelling infrastructures on road. In fact since the mission is known, the overall consumption of a fleet can be assessed in advance and the relative refuelling designed on purpose. Due to the considering number of such vehicles circulating in Delhi's area (50,000) and in the rest of India, it is evident that the hydrogen introduction can make an important shift towards cleaner transport, bridging the path to FC applications and zero emissions. Finally the ultimate aim of the project is to catalyse partnerships from private and public investors in order to continue and improve the fleet operation well beyond the end of ICHET funding (end of 2010) and establish a permanent transport service with a proper infrastructure. Three-wheelers are a popular mean of transport not only in India but also in other Asian countries, hence the success of the application of such hydrogen fleet has a big value also in light of its replication potential.

## References

[1] HY-alfa Project: development of a prototype of a three-wheeled vehicle Hy-alfa under the Alfa platform (CNG based) of M&M, jointly carried out by M&M and IIT Delhi.

[2] L. M. Das "Hydrogen engine: research and development (R&D) programmes in Indian Institute of Technology (IIT), Delhi" International Journal of Hydrogen Energy, Volume 27, Issue 9, September 2002, Pages 953-965

[3] L. M. Das, Rohit Gulati, P. K. Gupta "Performance evaluation of a hydrogen-fuelled spark ignition engine using electronically controlled solenoid-actuated injection system" International Journal of Hydrogen Energy, Volume 25, Issue 6, 1 June 2000, Pages 569-579

[4] L. M. Das, Rohit Gulati, P. K. Gupta "A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels" International Journal of Hydrogen Energy, Volume 25, Issue 8, 1 August 2000, Pages 783-793

# Horizon Hydrogène Energie : 19 Partners for Breakthrough Innovations on Early Markets

**Marianne Julien, Laurent Allidiere**, Air Liquide Hydrogen Energy, France

## Introduction

Early hydrogen energy markets offer opportunities to optimize and reduce the cost of technologies, introduce codes and norms adapted to the use of hydrogen in small quantities and raise public acceptance of the use of hydrogen outside industrial fences.

These markets offer a natural path towards the transportation markets for players such as Air Liquide and its partners, willing to build know-how and reputation and be ready for a wider use of hydrogen and hydrogen fuel cells.

Around this vision, 19 French partners have built the “Horizon Hydrogène Energie” Program” in order to leverage their competences and resources to build competitive offers to early customers as soon as 2012. Partners are industrial companies, technology associations and academic research centers.

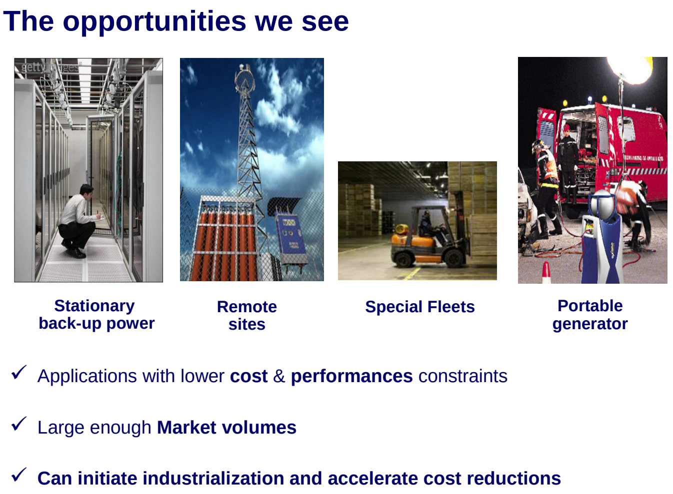
This 7-year innovation Program has a total budget of 190 M€ and is financed by the industrial partners (65%) and by OSEO Innovation (35%). OSEO Innovation is a French Agency leveraging innovation by private companies by bringing methodology and sharing financial risks.

More than 200 experts are directly contributing to the seven work packages of the Program.


## Do early markets really exist?

Early hydrogen energy markets have been identified and qualified in various sectors such as telecommunication, datacenters, medical centers, construction…

Targeted customers' need is the reliable production of electricity either for stationary use in places or at times where electricity from the grid is not available, or for mobile use when electrical batteries do not provide the autonomy required.




By integrating one of our different types of fuel cells, one of our three hydrogen storages with a customized logistic and maintenance service, we aim at building complete solutions to address customer needs at the lowest total cost of ownership.

Market studies for Europe show great potential for the substitution of existing technologies through fuel cell solutions providing cost reduction targets are met and/or special institutional support to the deployment of the technologies are put in place, such as tax credit have been implemented for use of fuel cell in forklift in the United States.

**Table 1: Data communicated in this table have been compiled by Air Liquide Hydrogen Energy using various information sources. They are shared to support our communication and do not engage Air Liquide responsibility.**

| Market Segment | Solution characteristics | Estimated European market size in 2015 (1) | Driver for introduction of fuel cell type solutions |
|---|---|---|---|
| Off-grid equipment<br>Telecommunication infrastructure, highways, sensors … | Baseload electricity 0.5 to 5 kW | 50 M€ opex/year | Total cost<br>Reliability<br>Carbon footprint |
| Back up service for critical equipment | Reliable peakload fuel cell with adapted H2 storage size | 200 M€ opex/year | Autonomy and reliability |
| Special Fleet of utility vehicles | H2 fuel cell "range extender" feeding an electric engine | 500 M€ opex/year | Total cost<br>Time for tank refilling |
| Portable electricity generators | Robust, easy to handle compact equipment up to 5 kW | 30 M€ opex/year | Total cost<br>Reliability<br>Safety perception H2 logistics |

**Where are breakthrough innovations required?**

Several hundreds of hydrogen fuel cells operating in the middle power range required for the early markets described above are now produced and sold through the world every year.

**Fuel Cell Cost**

Reducing costs while maintaining a high reliability and offering a large range of operating conditions (power produced, temperature…) is the challenge the H2E Program is focusing on. Systematic standardization of components is investigated in relations with critical component suppliers.

**Efficient production and logistics**

Production: About 60 industrial hydrogen production sites are operating today in Europe and constitute the current potential sources for the delivery of hydrogen to fuel cell applications. Large Steam Methane Reformers can produce up to 150 000Nm3 hydrogen per hour from Natural Gas. Their technology and process design are constantly evolving to optimize efficiency, reduce CO2 emissions and be ready to cost-effectively capture CO2 when CO2 underground storage sites will be accessible.

New decentralized production sites, using electrolysis equipment or small Steam Methane Reformer fed with biogas are also required to further reduce the carbon footprint of the complete solutions.

High pressure composite cylinders: the fact that hydrogen can be stored is a real advantage over electricity and electrical batteries and the degree to which we can store hydrogen in a safe and cost-effective manner will partially determine the share it will take in our future energy infrastructure. Nevertheless, technological and regulatory ruptures are required to build and operate composite cylinders. They can already now be investigated through the deployment of solutions on early markets.

The composite cylinders will also be used in the short term to transport hydrogen from centralized source to the point of use. Their design is optimized to reduce transportation cost and ensure operational flexibility.

Pressure regulation system

Using high pressure (up to 700 bar) to reduce the size of hydrogen storages requires advanced pressure regulation system and special safe connection device between the storage and the fuel cell. Air Liquide teams have worked within the HyChain European Project is designing such systems. Our goal now is to further reduce the cost of the equipment by optimizing the design while working with manufacturing experts.

**Social acceptance and RCS**

However, if breakthrough innovations are one of the key factors of the hydrogen early markets success, the public acceptance is another one. In order to facilitate the technologies introduction on the early markets, the hydrogen industry needs to convince society of the value of the technological innovations (social acceptance) and implement regulations, codes and standards (RCSs) with the authorities for daily use.

RCSs need to evolve from the current industrial hydrogen standards to lighter and easier procedures for uses of smaller quantities in our daily environment. On the other hand, hydrogen is almost unknown and unreferenced within the general public. Therefore, creating the conditions of hydrogen acceptance amongst the general public can be summarized as to make people climb one or more of the 4 levels of the so-called ‘social acceptance ladder’:

1. **Opposition/Ignorance**: the interlocutor is opposed to hydrogen and/or its applications as a whole, or simply does not know hydrogen or its applications.
2. **Acceptability**: the interlocutor is not against the use of hydrogen by a third party.
3. **Use**: the interlocutor himself uses hydrogen or one of its applications.
4. **Purchase**: the interlocutor is ready to acquire a product that uses hydrogen as an energy vector.

The H2E program encompasses those two aspects (social acceptance and RCS) as essential elements of markets creation and growth.

### To conclude

Early markets offer opportunities to anticipate some of the breakthrough innovations required for the wider use of hydrogen in our energy infrastructure, especially for transportation. Breakthroughs are required in many domains: from product design, manufacturing, regulation and standards, to project management practices to include early users in the decision process to deploy H2 type solutions.

The “Horizon Hydrogen Energy” partners are organized to tackle those challenges, driven by the common vision that hydrogen and electricity need to become fast the main energy vectors of our economy.

# Strategies for the Commercial Introduction of Modular Low Power Fuel Cells

**Paulo Emílio de Miranda**, **Alfredo Laufer**, Universidade Federal do Rio de Janeiro, Brazil
**Hugo Villela de Miranda**, EnergiaH, Brazil

**Abstract**

The reality of the infrastructure in emerging economies brings the opportunity to build up a hydrogen compatible economy. For the Brazilian case, the fast development in many fields coexists with a considerable amount of potential renewable fuels available. Costs of energy distribution and of power grid maintenance throughout a continental size country may lead to a distributed generation system based in a diversified fuels matrix. This pathway drives attention to simpler low power fuel cell devices, with easier maintenance procedures, friendlily integration with small power demands, and the capability of being applied separately or integrated to deliver higher power demands. Big cities and small distant agriculture based locations, such as Rio de Janeiro or rain forest extractive communities, could be able to produce fuel and energy in their own infrastructure projects. This article presents a market roadmap for the commercial introduction of direct oxidation type solid oxide fuel cells in Brazil, specifying fuel cell technological features and the specificities for each type of application, either in grid connected or in stand alone low power electric energy generation.

## 1 Introduction

A reliable source of Energy is one of the most important conditions to support development and growth. The distribution of energy in a continental nation such as Brazil is an expensive and difficult challenge. Local energy production is viewed as the best alternative to provide or to balance energy supply for small and standard demands, such as, small villages and extractive or agricultural communities. Local production may become of economic interest, mostly due to the costs of building, expanding and doing maintenance work on transmission lines of energy.

The Federal Government, using the regulatory agency for the electric market, has imposed some goals for the companies that are authorized to generate, transmit or supply electric energy in Brazil. To regulate those goals, the Federal Energy Regulatory Agency (ANEEL, in Portuguese) has made the Resolution nº 83/2004, establishing the conditions for being accepted as part of a program to generalize the energy supply.

Some developing countries, such as Brazil, still need to build an important part of the necessary infrastructure to support their economic growth. These characteristics allow the development of a multi source energy generating system and give opportunity to implement and test fuel cell devices. To develop these markets there are some opportunities and difficulties. We began to demonstrate some of those opportunities, analyzing initially the technical capability of the country in that area, understanding some configurations and elements necessary for the technology implementation and exploring some initial markets that are already able to receive this technology.

## 2 Technical Development in Brazil

Most part of the technical development is been made in the Federal Universities. There are no more than 3 companies developing solid oxide fuel cells and, those companies, have their development being made in cooperation with universities or public research centers. The reason for this is strongly based in the federal system of tax regulation in Brazil that provides public universities and research centers with technical and economic resources allowing companies to have a lower cost of research when in cooperation with them.

In order to support a market appropriation of this knowledge generated in the research centers, the developing countries need to invest more money and effort in generating an environment that articulates the R&D programs, research centers and industries, creating networks capable of assimilating, in a systemic way, new emerging technologies, generating new competences and abilities [1].

Furmana et al. [2] support that a nation infrastructure driven for innovation requires a series of human and financial factors. Those are based in the public polices for innovation in science and technology and the inherited economic sophistication.

Driven to those ideals, a national solid oxide fuel cells development network for (PaCOS, in Portuguese) was created in 2004. The network managed to generate human resources and some of the research groups achieved excellent results focusing in developing critical parts, such as the anode.

Important advances have been made recently on the development of parts, balance of plant systems and new materials for anode that support the direct oxidation of ethanol [3]. Those developments were facilitated by the more flexible federal regulations, with a good contribution from the law 11.196 [4], which established fiscal benefits for the private companies that invest in technology development in Brazil.

## 3 The Market

The electric market in Brazil possesses regulatory impositions in three different segments, the generation, the transmission and the distribution to the consumer. There are different companies for each segment, which are integrated or not in each region. All three companies or are obliged to invest in new technologies by contract. The distribution company, the one responsible for providing energy to the final consumer, has to attend some specific goals for energy distribution. This generates a market for distributed generation in Brazil.

Rural electrification was the biggest challenge. The problem was well attacked within the Program “Luz para Todos” (light for everyone) financed by the Federal Government, which imposed a tax in every single electric bill in Brazil to support the program costs, estimated for the year of 2009 in R$ 8.8 billions, having invested R$ 9.3 billion in 2008. This Program managed to attend the majority of the non-connected residences, but in order to maintain those transmission lines or to expand the capacity for new demands nearby the existing ones, required by the demand´s natural organic growth it will be necessary to expand the capacity of the transmission lines or to develop distributed generation.

The Program faced an organic growth of approximately 168.000 new connection points in 2009. To this number one has to add the demand for an expansion of the power capability to support small agro-industries. It is estimated to be at least 3.8% per year, based on an universe of 2 million new connection points achieved by the Program. This points out to a demand of 244.000 new connection points or more power yet needed on low power connection points. The growth rate of 3.8% is based on the average expansion of the domestic product for the period 2003-2007 [5].

The installation of new transmission lines or the expansion of the capacity of the existing ones is viewed as the probable solution to solve this problem. To address this issue, one should take into account the actual cost for building low power transmission lines that reached ~ R$26,000.00 per km in 2009. In this scenario, the admitted commercial target price of a fuel cell system may reach ~ US$ 3,000.00 per kW, taking into account a 2kW solid oxide fuel cell. This allows expediting the commercial initialization, considering that the usual fuel cell average commercial target price of US$1,500.00 per kW will no longer be an impeding barrier.

The application of small generation equipments has been the option in many cases. Borges and Carvalho [6] studied a typical situation for the most of the population that has no electric energy in their communities or houses. One of the most important factors is the fuel availability. Solar and wind based powers are conventional options but they depend on an energy storage system that presents problems with the life cycle of the batteries and the irregularity of the generation.

The ethanol production and distribution in Brazil is well established in every Brazilian State, both in large industries and in small familiar agro-industry production. Figure 1 shows the steep growth of the ethanol participation in the Brazilian Energy Matrix for 2009. For the first time products derived from sugar cane have overcome the hydroelectric energy generation.

Considering supplying the energy with low power fuel cell devices connected with the low power transmission lines already installed by the Program may be a way to provide the energy needed by small communities, offering any surplus energy to the grid. To make this a real opportunity, a new anode technology was co-developed by Coppe/UFRJ and EnergiaH [3]. It allows the direct oxidation of ethanol in the fuel cell. Table 1 shows the estimated market for ethanol solid oxide fuel cell in Brazil, considering the demands above discussed.

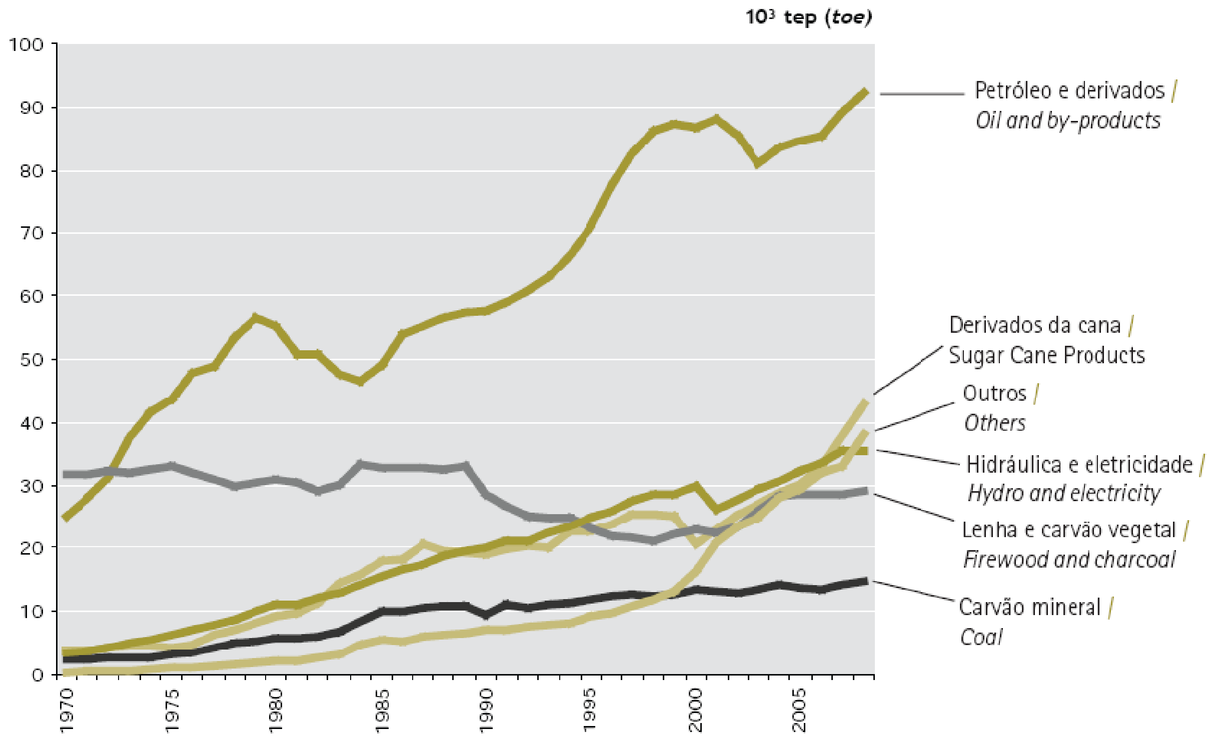



**Figure 1: Brazilian Energy Matrix Source: Brazilian Energy Balance [7].**

The model developed considers that a percentage of the annual estimated new connection points and additional power needed on existing low power connection points will be supplied with ethanol SOFC´s. 30% is considered to be the highest introduction level for the SOFC market of low power distributed generation in Brazil. The estimated purchase growth rate considers an initial demonstration of prototypes in 2011, to gain market confidence and make additional system developments. The present market has already a potential demand, but it is reasonable to believe that the companies will have a conservative purchasing police. In addition to that, the industrialization infrastructure, the needed technical trained personal and the supplier chain will not be achieved before 2013.

**Table 1: Ethanol Solid Oxide Fuel Cell Estimated Market.**

| annual demand | 244.000 | **Annual deployment** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | |
| rate of the annual demand supplied with ethanol SOFC | | 0,1% | 0,5% | 2% | 3% | 9% | 20% | 25% | 30% | Total |
| Number of 2kW ethanol SOFC´s | | 244 | 1.220 | 4.880 | 7.320 | 21.960 | 48.800 | 61.000 | 73.200 | 218.624 |

## 4 Conclusions

The present configuration of the electric energy system in Brazil, associated with the high production of ethanol, the already implanted distribution network for this renewable fuel and the new SOFC anode that allows the direct oxidation of ethanol, present an unique opportunity to develop and industrialize solid oxide fuel cells in Brazil.

For a 2 kW ethanol SOFC and if the electric regulations are kept as they are nowadays, there is a significant market for distributed generation with an attractive price. The biggest challenge in the present scenario is considered to be the technological development of a simpler balance of plant (BoP) and the demonstration of the first fuel cells prototypes.

### References

[1] Laufer, A. PhD. Thesis, Coppe/UFRJ, Rio de Janeiro, 2008.

[2] Furmana J. L.; Porter M. E.; Stern S. “The determinants of national innovative capacity”. Research Policy 31, pp. 899–933, 2002.

[3] Miranda, P.E.V.de; Venâncio, S.A.; Miranda, H.V.; “Process for the direct oxidation and/or internal reforming of ethanol, solid oxide fuel cell used for the direct oxidation and/or internal reforming of ethanol, catalyst and multifunctional electrocatalyst anode for the direct oxidation and/or direct internal reforming of ethanol”. INPI process no. PI0901921-9, 17/06/2009.

[4] Brazilian Federal Law. number 11.196, November 21, 2005. Accessed in February 25,2010: http://www.planalto.gov.br/ccivil_03/_Ato2004-2006/2005/LEI/L11196.htm

[5] Sicsú J., Castelar A., “Estratégias de crescimento e Desenvolvimento”. Instituto de Pesquisa Econômica Aplicada – IPEA, Brasília, 252 p., 2009.

[6] Borges, M.R.N.; Carvalho, P.C.M.; “Planejamento Energético Rural Assistido por Computador”. Eng. Agríc., Jaboticabal, V.29, N.2, pp.172-184, abr./jun. 2009.

[7] Brazilian Energy Balance 2009, reference year 2008. Balanço Energético Nacional 2009: Ano base 2008 / Empresa de Pesquisa Energética. – Rio de Janeiro: EPE, 274 p., 2009.

# HCNG – A Dead End or a Bridge to the Future?

**Corfitz Nelsson**, Swedish Gas Center, Sweden
**Christian Hulteberg**, Hulteberg Chemistry and Engineering
**Jacques Saint-Just**, H2 Plus Ltd.
**Mehrzad Kaiadi**, Faculty of Engineering, Lund University

## 1 Introduction

HCNG is a vehicle fuel which is a blend of natural gas and hydrogen in various proportions, typically 8-50 vol% hydrogen. Mixtures below 20% are often referred to as Hythane™. HCNG is can bridge the gap between traditional liquid fuels and hydrogen. By using HCNG as a transition fuel and taking advantage of the CNG existing infrastructure, it is possible to start building a hydrogen infrastructure at a minimum cost, even though dedicated hydrogen vehicles, on a large scale, are 15-30 years away, many critical aspects of the whole hydrogen chain as a vehicle fuel can be investigated right away in commercial HCNG operation. Besides this benefit as a transition fuel, HCNG has its own specific advantages in terms of noxious emissions and, if in addition, the hydrogen is produced from renewable resources, HCNG could also contribute to reduced GHG emissions.

## 2 History

Since the filing of the original Hythane® patent [1] in 1990, several demonstrations have been carried out in North America, often with limited commercial operation, (Denver, 1992, Montreal, 1995-1996, Thousand Palms, 1999 and on, Las Vegas, Phoenix, …) and more lately in Europe (Sweden, Italy) and Asia (India and China). HCNG was observed to have benefits in terms of the usual emissions (CO, $NO_x$, unburned hydrocarbons), although the performances differ for every specific situation, type of engine and operation mode. In the last decade, HCNG has been viewed also as a transition vehicle fuel towards hydrogen and renewables if the added hydrogen is “green”.

## 3 Fuel Properties

By adding hydrogen to CNG, the properties of the fuel changes in several ways. The most important factors are:

- Lower ignition energy and fast burning rate of HCNG makes it less resistant to knocks than CNG at constant λ.
- Lower heating value – higher consumption in terms of $Nm^3$ per km.
- Lower compressibility factor – fewer $Nm^3$ in a tank at 200 bar compared to CNG.
- Higher flame speed – faster combustion. higher engine efficiency.

Table 1 gives a few figures concerning the energy loss in the storage tanks at constant pressure.

**Table 1: LHV and compressibility factor for different HCNG mixes at 200 bar (Danish natural gas).**

| $H_2$ content | 0 % | 8 % | 20 % | 25 % | 30 % |
|---|---|---|---|---|---|
| LHV ($MJ/Nm^3$) | 43,8 | 41,3 | 37,6 | 36 | 34,5 |
| Change compared to CNG | 0% | -6% | -14% | -18% | -21% |
| Compressibility Z @ 200 bar | 0,75 | 0,80 | 0,87 | 0,90 | 0,93 |
| Change compared to CNG | 0% | -7% | -16% | -19% | -23% |
| Total energy compared with CNG | 0% | -12% | -28% | -34% | -39% |

The upper limit of the range loss is 12-15 % when using 8-10 % hydrogen and 30-40 % when using HCNG with 20-30 vol-% hydrogen. A potential higher engine efficiency when burning HCNG can compensate in part the negative changes in gas properties when comparing CNG and HCNG. As buses may be fitted with additional storage capacity without too much difficulty, HCNG appears more suited to public bus fleets than to passenger cars.

## 4 GHG Balance

A Well-To-Wheel (WTW) analysis of HCNG and CNG (EU-mix) has been performed and three ways of supplying hydrogen has been investigated: reforming of natural gas (EU-mix), electrolysis (EU-mix electricity) and electrolysis (renewable electricity).

**Table 2: WTW $CO_2$ emissions (g/MJ) for HCNG produced through different routes and with different hydrogen content.**

| $H_2$ content | 0 % | 8 % | 20 % | 25 % | 30 % |
|---|---|---|---|---|---|
| Electrolysis green electricity | 66 | 64 | 62 | 60 | 59 |
| $CO_2$ change | 0 % | -2,4 % | -6,4 % | -8,3 % | -10 % |
| Electrolysis EU-mix electricity | 66 | 70 | 77 | 80 | 84 |
| $CO_2$ change | 0 % | 6,1 % | 17 % | 22 % | 27 % |
| Reforming natural gas | 66 | 68 | 72 | 74 | 76 |
| $CO_2$ change | 0 % | 3,5 % | 9,7 % | 13 % | 16 % |

In terms of GHG reductions, the $CO_2$ emissions associated from production of hydrogen through reforming of natural gas or electrolysis of “grid” electricity can never be compensated through increased efficiency as that would require unrealistic improvements (10-15 % at 20 % $H_2$). Reforming of biogas has been suggested as a way for supplying green hydrogen but for that case it would be better to use the biogas as vehicle fuel directly. If the existing vehicles have problems with high emissions of methane, the introduction of HCNG could still reduce overall GHG emissions as methane is a very potent GHG and adding hydrogen to the CNG would improve the combustion efficiency and stability.

A cost-benefit analysis of HCNG versus CNG mixed with biogas to give the same $CO_2$-reduction as HCNG shows that biogas upgraded to vehicle quality (>97 % methane) can be produced for 2-2.5 €c/MJ. Hydrogen from grid electrolysis can be produced for 3.5-5 €c/MJ, clearly giving a cost-benefit advantage in favor of biogas.

## 5 Lund Laboratory Tests [2, 3]

The Division of Combustion Engines at Lund University, Faculty of Engineering has performed several tests using HCNG. Tests on a one-cylinder 1.6 liter engine back in 2002 showed that HCNG would improve combustion stability on low loads, the combustion time is reduced, $NO_x$ at very lean operation is reduced and that the effects of HCNG are reduced when using a piston that creates high turbulence. Full engine tests in 2003 on a 10 liter gas lean burn engine showed: approximately 2 % points higher efficiency and this is more noticeable when reaching lean limits, increased $NO_x$ emissions and reduced HC emissions, better combustion stability (lower COV). Tests with 25 % hydrogen on the same engine gave more or less the same results but it was necessary to change the engine mapping in order to run on 25 % hydrogen.

In 2008, they performed test of using 10 % hydrogen in a 9.4 liter Volvo G9 ($\lambda$=1) gas engine and the main conclusions are:

- The engine operated stoichiometric with CNG and HCNG according to the European Stationary Cycle and no significant changes in knock margins, efficiency and emissions were captured.
- Combustion quality is good when engine operates stoichiometric on CNG and the combustion duration is short enough which means using HCNG does not show benefits over CNG in terms of efficiency and emissions.
- Dilution limits (EGR levels) can be extended by approximately 10 %.

Additional tests on 25 % hydrogen where carried out late 2009. Since 2008, the engine had been fitted with new pistons with geometries designed to generate high turbulence which might have reduced some of the effects of HCNG. The results suggest that HCNG may not offer significant advantages over CNG in terms of emissions in vehicles equipped with modern stoichiometric engines with three way catalysts.

- Dilution limits (EGR) can be extended by 15 %.
- No significant changes are observed in efficiencies or knocking margins.
- Pre-catalyst emissions of $NO_x$ increase, while emissions of HC and CO decrease, most significant decrease is observed for HC because of the high H/C ratio of HCNG.

## 6 Sweden [4]

Two city buses were run in Malmö for about 160.000 km during 2003-2005. These were Volvo buses from 1996 with lean-burn engines. It was not necessary to modify the buses for running 8 % HCNG but for 20 % a new engine mapping was used. The fuel consumption was reduced for the HCNG case compared to CNG but there was no significant difference between using 8 % or 25 % hydrogen. On road emissions tests with 25 % hydrogen showed:

- Running uphill: 50 % reduction of HC, no change of CO and 200 %.$NO_x$ increase

- Constant speed: 30-50 % reduction of HC, slight increase of CO, fuel consumption down about 3 % and about 100 % increase of $NO_x$
- Acceleration from 0 km/h measured during 24 seconds: HC reduced by 50 %, $NO_x$ increase about 50 %, CO reduced by 30 % and 10 % lower fuel consumption.

The lower fuel consumption during the acceleration phase is interesting as many city buses do not run steady state for long times and most of the time it is brake, idle or acceleration.

## 7 Norway [5]

In Bergen, HCNG was demonstrated during late 2008. Early emissions tests show no reduction of HC and CO, a slight increase of $NO_x$ and a $CO_2$ reduction of 5 %, about half of that is due to increased efficiency and half due to lower carbon content in the fuel. The buses used lean-burn technology.

## 8 Italy [6]

Italy has almost 600.000 CNG cars on the road and more than 80 years of CNG experience. In 2008, Italy created a 10 M€ Hydrogen Platform Fund which includes development of HCNG applications. The plan is to build a network of stations out of lighthouse projects. HCNG is considered a bridge to future hydrogen technology and a few Agip stations can supply HCNG, such as the most recent one which opened in Milan in February 2010. Laboratory tests have showed promising results for HCNG which will be followed by road tests. Fiat has also showed the concept car Panda Aria which can run on HCNG with 30 % hydrogen.

## 9 Asia [7]

India has been pursuing CNG for reducing local pollutions and among the actions taken has been a mandate for public transport in New Delhi to use CNG. Due to the increasing number of vehicles, pollution levels have been steadily rising. HCNG has been introduced as an option to make CNG vehicles even cleaner and the Society of Indian Automobile Manufacturers together with Indian Oil Company has been investigating this issue. Their research shows that HCNG with 18 % hydrogen gives the greatest reduction of $NO_x$ and the lowest power reduction. The next step is to convert 50 vehicles, test them and then introduce HCNG as a mainstream fuel.

## 10 Current US Status [8, 9, 10]

The arguably largest breakthrough favoring the use of HCNG in the US came in August in 2009 as the California Air Resources Board (CARB) granted certification for the Ford 6.8L V10 engines used in the Ford model E-450. The vehicles are converted by BAF Technologies (US) in cooperation with the Hythane Company LLC (a US subsidiary of Eden Energy, Australia). The use of HCNG in this engine has been reported to reduce the non-methane hydrocarbons by 40%, the methane emissions by approximately 50% and a 70% reduction of particulate emissions compared to the natural gas version of the engine. The certification indicates that commercial sale of HCNG vehicles can commence, not limiting the use of the fuel to controlled demonstration projects. Then engine calibration was performed for the inclusion of the vehicle in a HCNG project at the San Francisco airport. In the project, 27 Ford E-450 will be converted to HCNG and a refilling station will be constructed at the airport by the Hythane Company LLC.

Additional activities include a 4 year DOE program in Las Vegas, where nine compressed natural gas vehicles were converted and driven between 5 500 km and 60 000 km with varying results. In general there were low to zero maintenance issues after the first conversion bugs were sorted out. The fuel consumption varied between the different vehicles, some vehicles had a 20% reduction while some had a 30% increase in fuel consumption. Operating experience also include poor performance (lack of power and misfiring) when the hydrogen level in the natural gas was low and knocking with the possibility of serious engine damage at high hydrogen concentrations. Most of the vehicles showed zero $NO_x$ emissions after conversion. Even though the program has been terminated, the cars are still being operated.

## 11 Safety

Safety related problems that could be associated with HCNG are essentially material compatibility, leakage and hydrogen embrittlement. In conjunction with the Malmö field tests, safety studies were performed on two bus models and these showed no major obstacle for using HCNG in terms of material and component compatibility. Worst case scenario, i.e. exposure to pure hydrogen was used when examining material compatibility. Of course, these results cannot be generalized to all vehicle models but it is an indication that there are no major showstoppers in the vehicles. A second safety study on newer buses also indicated that most high-pressure parts are compatible with 100 % hydrogen.

Another issue affecting the possibilities to introduce HCNG is the lack of standards. Since HCNG covers a range of mixtures and since none is a specified fuel, there are no standards, codes, test procedures etc. covering HCNG. Because of that, no vehicles are certified for HCNG operation, making it very difficult to introduce HCNG in any larger scale than small demo projects. New vehicles cannot be certified for HCNG as there are no regulations and if they cannot be certified, they cannot be sold, in Europe at least. In the US, there is some ongoing work within NFPA to include HCNG in NFPA 52, which, when in place, could clearly be beneficial for introducing HCNG vehicles.

## 12 Discussion

In cities where local pollution is a major issue, HCNG can reduce emissions of $NO_x$, CO and HC and help improve air quality. However, a few conflicting observations have been reported in that respect. This is not so surprising in view of the fine engine tuning required to reduce overall emissions and the sensitivity of the emissions to the mode of vehicle operation. Therefore, the benefits of HCNG must be appreciated on the basis of the statistics built on the numerous observations obtained over the years rather than on isolated results obtained in conditions not fully described. In lean burn vehicles, HCNG offers clear advantages over CNG:

- Emissions of CO and HC will likely be reduced without the need for engine optimization or tuning.

- Significant $NO_x$ reductions can be obtained with leaner operation, but at the expense of efficiency
- Efficiency gains are possible but these will be modest, especially if low $NO_x$ emissions are targeted (trade off).

For stoichiometric engines, the environmental and technological issues are different. Today, the majority of the new CNG vehicles are using $\lambda=1$ engines with TWCs and have very low emissions. For heavy-duty vehicles, the HCNG specific technological role could exist at the EGR level but considering the levels of the regulated pollutants for the coming years, HCNG does not offer a significant advantage compared to CNG in this respect.

Considering the reduction of $CO_2$ emissions which is one of the priorities today HCNG may have an edge over CNG from a Well-To-Wheel perspective if the added hydrogen is green. That hydrogen may originate from biomass gasification or from water electrolysis using excess renewable electricity in order to achieve a reduction of GHG emissions. However, if only a $CO_2$ reduction is targeted, HCNG maybe not the right tool as 30 % of hydrogen gives only a $CO_2$ reduction of 10 %. In many area of the world, this can be achieved more easily by adding 10 % of biogas which would be available at a much lower cost and does not lead to any range reductions.

Given all the aspects discussed previously, HCNG must be considered best suited for markets where lean-burn vehicle engines are in use and the number one issue is local pollution, not $CO_2$ reduction. This represents a huge market in emerging economy countries. In the smaller markets where optimized CNG technology is in use, the main benefit of HCNG is its value as a transition fuel permitting a hydrogen distribution infrastructure to be set up at a realistic pace and acceptable costs. That benefit, combined with the energy issue awareness impact in public transportation, cannot be overestimated.

## References

[1] F. Lynch and R. Marmaro, to Hydrogen Consultants, Inc., US Patent 5139002, August 18, 1992- Special purpose blends of hydrogen and natural gas-.

[2] M Kaiadi, P Tunestål, B Johansson: “Using Hythane as a Fuel in a 6-Cylinder Stoichiometric Natural-gas Engine” SAE Technical Paper 2009-01-1950.

[3] M Kaiadi, How HCNG with 25% hydrogen can affect the combustion in a 6-Cylinder Natural-gas Engine, SGC Internal Report.

[4] Owe Jönsson, Utveckling och demonstration av användning av metan/vätgasblandningar som bränsle i befintliga metangasdrivna bussar. SGC Rapport 170, 2006.

[5] Tomas Fiksdal, Alternative drivstoff, Seminar ”Gassdrift av busser og tyngre kjøretøy”, 29 oktober 2008.

[6] Hydrogen in the city – sustainable urban transport, EHA session at Sustainable Energy Week 20080128-20080201.

[7] Neha Lalchandani, BREATH OF FRESH AIR SOON? New tech set to turn CNG greener, Hydrogen Blend To Curb $NO_x$ Emissions. The Times of India 2010-02-18.

[8] Eden Energy Press Release, California Air Resources Board Grants Certification for Hythane® Engine, http://www.edenenergy.com.au/pdfs/20090728%20ASX_Announcement%20-%20CARB%20Approval%20Final.pdf, 2009-07-28.

[9] NGV Global News, Hythane Calibration for Ford 6.8L V10 Engine Certfied by CARB, 2009-08-12, http://www.ngvglobal.com/hythane-calibration-for-ford-6-8l-v10-engine-certified-by-carb-0812

[10] DOE Report, Hydrogen-Enhanced Natural Gas Vehicle Program, Dan Hyde, DE-FC36-04GO14263

| | |
|---|---|
| **SA** | **Strategic Analyses** |
| SA.1 | Research & Development Targets and Priorities |
| SA.2 | Life-Cycle Assessment and Economic Impact |
| SA.3 | Socio-Economic Studies |
| SA.4 | Education and Public Awareness |
| SA.5 | Market Introduction |
| SA.7 | Regional Activities |
| SA.8 | The Zero Regio Project |

# Hydrogen and Fuel Cells around the Corner – the Role of Regions and Municipalities Towards Commercialization

Andreas Ziolek, Marieke Reijalt, and Thomas Kattenstein

**Abstract**

New clean energy technologies such as hydrogen and fuel cells are seen as a potential solution for the world wide future energy and transportation needs. Many development and funding programs exist worldwide which vary from region to region. The need for a better coordination of these programs and the preparation of a long-term commercialization strategy is crucial for the effective support and the effective integration for these technologies at a local level. Regional and local organizations have to be involved at an early stage in the development of new funding frameworks and relevant programs for hydrogen and fuel cell technologies, such as HyRaMP.

# Platform for Promoting a Hydrogen Economy in Southwest Europe: the HYRREG Project

**Rei Fernandes**, Instituto Superior Técnico, Portugal
**Carmen Gonzalo**, Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón, Spain
**Juan Manuel García**, Universidad Rey Juan Carlos, Spain
**Esther Chacón**, Instituto Nacional de Técnica Aeroespacial, Spain

## 1 Introduction

The effective promotion of hydrogen technologies is best achieved when there is a strategy and a well defined accepted plan. In order to promote a hydrogen-based economy the HYRREG project, funded by the program of cooperation of the territorial area of Southwest Europe (SUDOE), is developing a platform to generate hydrogen-related projects and a roadmap to enhance regional competitiveness and development of industry in the fields of hydrogen and fuel cell technologies. The project focuses on SUDOE which is comprised of 30 regions and autonomous cities representing about 770 120 km$^2$ (18.2% area of EU-27) and 61.3 m inhabitants (12.4% of EU-27).

The idea of a specific roadmap for SUDOE had its origin in “HyWays,” a project undertaken by research institutes and industry, funded by the European Commission [1]. Although France and Spain were analysed in the HyWays project, regional stakeholders participating in HyWays saw the need for a more specific and thorough analysis focussing on the actual conditions by regions in SUDOE. The HyFrance project has already produced a roadmap for France and Portugal too has made progress towards a national roadmap through the HiPo project [2,3]. It is anticipated that the implementation of hydrogen technologies will contribute towards diversification and technical adaptation involving a large number of industries and SMEs, affording opportunities to develop new innovative products and services.

Much of the emphasis to date has been on the improvement of hydrogen technologies, but little has been done to transfer existing knowledge and expertise to SMEs and to build interregional networks of cooperation. The HYRREG project therefore established as its main objectives, (i) the establishment of a platform for the promotion of R&D in cooperation with companies and for generating projects related to hydrogen, (ii) the development of a regional hydrogen roadmap for SUDOE and (iii) the dissemination of the project findings. These measures were designed to increase collaboration between the offices of technology transfer and other agents at both national and international levels and to raise awareness in society of the benefits of using such technologies.

## 2 Characteristics of SUDOE

Portugal and Spain have some of the highest energy dependencies in Europe, surpassed only by Italy, Ireland, Cyprus, Luxembourg and Malta in the European Union. In 2007 the levels of dependency were 82.0% and 79.5% respectively whereas that for France was

50.4%. Eurostat data for the year 2007 indicate that fossil fuels (hard coal, lignite, oil and gas) account for 80% and 84% respectively of the gross inland consumption of energy for Portugal and Spain [4]. In France the equivalent figure is 53% because of the large share of nuclear energy (42%).

Renewable energy sources are growing steadily as sustainable policies to reach the EU 20-20-20 targets are being implemented. Whilst the installed capacity for electricity generation from renewables in EU-27 grew 54% in the decade to 2007, 58% of that capacity was concentrated in just four countries (Germany, Spain, France and Italy). The increase was mainly due to wind capacity and SUDOE accounts for over 35% of that capacity with contributions from Spain (16,740MW), France (3,404MW) and Portugal (2,862MW). HYRREG therefore believes that there is a good basis for supporting the development and introduction of hydrogen-based technologies in the region especially with respect to the use of hydrogen for storage. For Portugal and Spain the development of renewable energy is particularly important as both countries can be considered as “energy-deficient islands” due to their high energy dependency.

## 3 The HYRREG Platform

The purpose of the HYRREG platform therefore is to consolidate hydrogen-related activities in the region in order to promote cooperation between research institutes and industry. The approach is somewhat similar to that of the Hydrogen and Fuel Cell Technology Platform and the development of a strategic research agenda, a deployment strategy and an implementation plan, but also includes a proactive strategy of engagement. Links have been established with several institutions providing different support mechanisms within SUDOE. Agreements of cooperation have been signed with AeH2 (the Spanish Hydrogen Association with a membership of 36 enterprises, 17 research centres and 84 individual members) and the Spanish International Innovation Unit (UII) of Energy. Other institutions that are being approached include APPICE (the Spanish Association for Fuel Cells with 25 companies and 56 individual members), AP2H2 (the Portuguese Hydrogen Association with 17 companies), UII of $CO_{2,}$ PTE-HPC (the Spanish Platform of Hydrogen and Fuel cells comprised of 49 companies, 87 research, public and private entities), Aragonese Net of 7th Framework Programme, Agencia Andaluza de la Energía and the regional governments of Aragon, Castilla la Mancha and Comunidad de Madrid, An agreement has also been signed with PAC-H2. All these collaborators appear on the HYRREG website as “Collaborator Entities”. Cooperation with regional governments offers a means of rapid implementation of hydrogen technologies initially as a bottom-up approach to disseminate and develop activities at local, regional and then national level but always with a vision for national strategies for hydrogen technologies.

HYRREG has been successful in launching a total of twenty five projects of which eleven are national, five European, three interregional (FR-ES) and two with Iberoamerica. The institutions involved will appear in a HYRREG catalogue containing details of stakeholders [5]. The collaboration with these entities is bidirectional as common objectives are followed, namely; sustainable development by means of renewable energies and/or hydrogen technologies. An online database of technologies and product opportunities in the field of hydrogen is being created for SUDOE and across Europe to help companies in the region to access international markets. The database allows one to search for new technology offers or requests and to find international partners. HYRREG has collaborated with the Spanish Hydrogen and Fuel Cells Platform, the Spanish Ministry of Science and Innovation instrument for promoting hydrogen technologies, in the National Plan for R&D 2008-2011 to define strategic lines related to hydrogen technologies. The Portuguese Hydrogen Association is currently preparing a proposal to define the role of hydrogen in the national energy plan.

A catalogue listing profiles of companies or institutions working on hydrogen and fuel cells, their research lines and fields of interest, is currently under preparation as an aid to establishing links between the entities for the purpose of cooperation. The catalogue, which will be posted on the project website, will include technology transfer profiles highlighting technologies offered and those sought in the region. Other measures adopted to enhance cooperation between companies, universities and research institutes include a brokerage event at GENERA, the energy fair held in Madrid in May 2009 with more than 150 participants, of which 30-35% were directly related to hydrogen technologies. Presentations of the project have been made at HYCELTEC, an international conference held in Vila Real in Portugal, at special seminars held by AeH2 where there were about 100 attendees from the energy and research sectors and at the H2-Power Expo in Zaragoza.

## 4 SUDOE Roadmap

The SUDOE roadmap will focus on stakeholder preferences and country specific conditions such as availability of resources as well as the characteristics of the current and future energy systems in the region, applying a mainly qualitative analysis. The methodology consists of an iterative enquiry process of selected stakeholder groups involved in the energy sector. A questionnaire has already been launched and answers are in the process of being analysed. Following a SWOT analysis and a review of indicators selected by HYRREG, workshops will be held to produce a draft roadmap. Subsequently, after further analysis and the evaluation of hydrogen chains and deployment strategies a second version of a SUDOE roadmap will be produced.

## 5 Opportunities and Challenges within SUDOE

Whilst renewable energy technologies are quite well developed and already in common use, the intermittent nature of renewable sources means that they cannot be relied upon for base load. However the availability of an efficient means of storage coupled with energy management (balancing energy demand with energy supply) could significantly reduce the energy dependency in SUDOE. Hydrogen could provide a solution to the problem of energy storage. If renewable energies can be coupled to energy storage systems, they will become available to offset the growth in network capacity. Furthermore, they would become multi-purpose, decentralized producers of electricity or hydrogen for fuel when the automotive industry enters mass production of hydrogen-fuelled vehicles. In the short term, marginal but significant benefits can be obtained by improving dispatch ability and offering reserve power and grid services. Other opportunities are being identified through a survey of more than 250 stakeholders (150 Spanish, 70 Portuguese and 38 French). The responses indicate that hydrogen can be extremely valuable in SUDOE not only for energy storage when there is an excess, but also to supply remote areas and the islands in SUDOE with energy and as an alternative fuel for transport. These are the main end-use applications that hydrogen is envisaged to have in SUDOE.

## 6 Technology Watch Reports

Stakeholders in SUDOE have identified topics for "Technology Watch Reports" (TWR) that will summarize the state-of-the-art in a particular field providing extracts of relevant information on technology trends, developments, inventions, potential partners or competitors, emerging technological applications covering regulatory aspects and markets which can influence the success of a technological innovation. The preliminary list of 16 topics for the technology watch reports include mainly hydrogen production from renewables both with and without hydrolysis; from wind power through electrolysis; from high temperature solar energy using thermochemical cycles in combination with high temperature electrolysis; small scale reforming for refuelling stations; decarbonisation of methane and on-board production via chemical hydrides, reforming, ammonia and boranes. Other topics focus on PEM technologies (high temperature, alkaline PEM for electrolysis) and the state-of-the-art of SOFC. Two more topics for a state-of-the-art analysis are new batteries concepts *vs.* development and international normalisations and regulations concerning hydrogen storage and transport. Work has already begun and some topics are available on the website (www.hyrreg.eu). The report on small-scale reforming systems for hydrogen refuelling stations, for example, describes the different technologies and compares them, covering steam reforming, partial oxidation and autothermal technologies. It includes suppliers and takes into account market factors such as hydrogen production capacities, costs, fuel quality, size, load variation and star-up behaviour with some details of demonstration projects in different countries. Other reports cover patented technologies to assess their potential value by comparison with the market and by defining their strengths and weaknesses. In one case HYRREG estimated the value for licensing a patent and offered to help the research group negotiate the IP contract. These are just two examples of different technology watch report and their usefulness in technology transfer.

## 7 Other HYRREG Activities

The HYRREG project embraces some horizontal objectives including the training of technicians from Technology Transfer Offices (OTRIs) that are specialized in different specific sectors such as hydrogen technologies. Technicians from OTRI in Aragon have already gained some knowledge of hydrogen technologies through the new projects that have been launched. The level of action in terms of technologies involved has increased both within enterprises and in research centres. All the partners are necessarily in contact with companies and research centres for activities related to the work packages. Furthermore HYRREG plans awareness campaigns to highlight the advantages of using hydrogen technologies with a view to encouraging local authorities to start demonstration projects that are informative and that have a high social impact.

To monitor progress, HYRREG has established a number of indicators based on the activities to be carried out by the partners of the consortium. All the tasks and actions have been enumerated and quantified to facilitate an assessment of progress.

## 8 Conclusions

Although the potential for hydrogen applications is virtually unlimited, transportation and early markets in portable applications are expected to be near-term drivers for a broader use of hydrogen, whilst stationary application related to wind energy and other renewables such as solar photovoltaics are promising. The inherent variable nature of wind and solar energy is limiting and poses problems of integration for market and grid operators. This may slow down their development in electricity markets where they already have a high penetration, but storage systems can provide a solution, allowing renewable energies to be closer to conventional energies. The HYRREG project grew from this scenario, based on two main activities, a platform to promote projects and a roadmap to define opportunities and strategies for the SUDOE region in new technologies in the energy, automotive, electronics and chemistry sectors. HYRREG is actively facilitating the implementation and use of sustainable technologies in agreement with European policies through interaction with the main regional stakeholders related to hydrogen technologies in industry, research centers, SMEs and Regional Governments by means of seminars, agreements, launching of projects, technology watch reports and brokerage events in a coordinated fashion to take advantage of market opportunities with innovative products and services.

## References

[1] HyWays – Hydrogen Energy in Europe, Integrated Project under the 6th FP of the European Commission, 2004-2007, http://www.hyways.de

[2] Agator, J.M., and S. Avril, 2006. Towards a French Hydrogen Energy Roadmap: the HyFrance Project. WHEC 16 / 13-16 June 2006 – Lyon, France.

[3] Pimenta, R and Fernandes, T., 2008. Scenarios for the future of hydrogen in Portugal – the results of the Project HI-PO. WHEC 17 / 15-19 June 2008 – Brisbane, Australia.

[4] Energy, transport and environment indicators, 2009. Eurostat Pocketbook, 2009 edition. European Commission, Luxembourg.

[5] HYRREG Catalogue of Technology Profiles 2009 Edition, www.hyrreg.eu

# HYCHAIN: Assessment of the Development and Deployment of Several Fleets of Small Hydrogen Powered Hybrid Vehicles

**Maxime Dupont***, Air Liquide, France
**Philippe Paulmier**, AXANE, France

The HYCHAIN MINI-TRANS project is one of the three leading EU demonstration projects for hydrogen as an alternative fuel (2006-2011). HYCHAIN MINI-TRANS is an integrated project of 24 partners that received 17 M Euro funding under the EU FP6 and is coordinated by Air Liquide S.A.

The project focuses on the development and the deployment of several fleets of small hybrid vehicles (50) powered by hydrogen fuel cells. It includes fuel cell tricycles, utility vehicles, buses, wheelchairs and scooters. These vehicles are deployed with the accompanying hydrogen refuelling infrastructure in four regions of Europe: Grenoble/ Rhone-Alpes (F); Modena/ ER (I); Soria/C&L (S); Emscher Lippe/NRW (D).

Important lessons have been and will be learned on the experience of deploying fifty fuel cell vehicles, thus providing a precious feedback to position hydrogen as an alternative energy carrier for the transport market. The objective of this paper is to address the challenges which have arisen during the development phase and at the beginning of the operational experience.

We have limited the discussion to the main lessons drawn from the experience in five critical areas: technology; commercial feed back; homologation process; public acceptance and the management approach of a large scale complex project, such as HYCHAIN.

## 1 Technology and Industrial Approach

Developing and deploying several fleets of innovative hydrogen small size vehicles in five years became quickly very challenging. Many tasks had to be done in parallel and, in many instances, these tasks were interrelated. The risk analyses, the homologation approach, the desired level of industrialization, had an impact on the technological definition of the products. Many loops of design reviews were necessary and, inevitably, this delayed the development of the products, thus their launch on the market.

A key challenge was to have a light weight, high pressure, hydrogen cartridge with a quick connection in order to allow for an easy and safe even exchange of the H2 tanks. It became rapidly an ambitious objective as this meant developing jointly a 700bar composite Type IV cylinder and the associated high pressure connection. Many tasks had to be achieved in parallel, revealing their own difficulties. Currently the project is in the process of resolving the last reliability issues by doing field tests with a demonstration vehicle at 500bars. This is the

* Corresponding author, email: maxime.dupont@airliquide.com

pressure for which the highest reliability ratio was obtained. We are currently monitoring the last two important parameters for high pressure systems: tightness solutions and high precision mechanisms. The difficulties to elaborate such a cartridge were probably underestimated but we did managed to acquire valuable knowledge on high pressure design, manufacturing, and testing that will be used to develop the next generation of quick connect high pressure valves and high pressure composite cylinders.

To deploy the Hychain vehicles, Air Liquide defined and validated hydrogen cartridges using conventional 300bar components.  All the vehicles, except the Midibus which uses fixed tanks, are built around homogeneous systems, using standard components and generating some industrial savings. Yet, the limited quantity of vehicles, the limited numbers of suppliers, and the absence of common standards – at that time – kept the costs at a high level compared to the project targets and obviously, there cannot be any comparison with the automotive industry. This had an impact on the commercial side.

## 2 Homologation – Certification

At the start of the Hychain project, no standard or directive was in place to support the homologation process for hydrogen vehicles. Some drafts directives existed and were used by the local authorities to assess the vehicles. So for Hychain, the homologation became vehicle specific, then country specific, and sometimes, contact specific. This generated a multiplicity of contacts, requirements, tasks, tests and reviews. The homologation of the utility vehicle, for instance, lasted significantly longer than planned, delaying furthermore the commercial phase and the start of the deployment.

Despite these difficulties, HYCHAIN was successful to obtain homologation for all vehicles in most countries: Certification for the wheelchair and the Cargobike; Homologation for the utility vehicle and the Midibus.

The Midibus was already homologated in Germany and Spain using a vehicle single type approval approach.

**Wheelchair:**

The HYCHAIN wheelchair, as Class 2 medical device, was auto certified by the manufacturer. The standards applicable to electrical wheelchairs were the starting point for the certification. The hydrogen aspects were treated with a certified laboratory (TUV-Sud) which tested the wheelchair according to the standard for electrical wheelchairs and analyzed the H2 system according to HYCHAIN's risk analysis and the installation's requirements described in the draft EIHP. The ISO 7176-21:2003 conformity certificate for the HYCHAIN wheelchair was obtained in June 2009.

**Cargobike**

The Cargobike was also auto-certified. The existing European directive, exempts from model authorization for the two-wheeled or three-wheeled vehicles. The vehicle integrator declared conformity according to the draft standard for electrical bikes (prEN 15194). Regarding the H2 system, the approach was based on the risk analysis performed by the HYCHAIN partners during the project.

**Utility vehicle**

The process for the UV has been long and demanding. The path chosen by the vehicle integrator was to homologate the utility vehicle country by country through a small series, light homologation request. It was a single vehicle type approval, not a global approach. This resulted in multiple exchanges with the authorities and in many cases additional tests on the base vehicle had to be performed at each request. In our case, most of the discussions were focused around the base vehicle and not around the Hydrogen system or the fuel cell systems. This is an important lesson: the choice of the vehicle base can impact the homologation strategy.

It is clear that the coming European directive on fuel cell vehicles will make the homologation process global as it will be accepted as a reference to work with by all the European countries and all manufacturers (vehicles and components).

**Scooter**

At this point of time, the scooter is starting its homologation process using a single vehicle type approval approach for an operation in Spain. Its development took much more time than foreseen due to the required high integration level. Building a fuel cell scooter is not only very challenging from a design perspective but it is also difficult for safety reasons. The fuel cell integration issues and the late availability of the high pressure Hydrogen cartridge (required to provide an adequate driving range) caused a major delay. In the end, the deployment of the scooter was not possible since it was not homologated at the start of the deployment. However it was decided to complete the homologation and to capitalize on the experience from this process.

**Authorities**

With the exception of Germany, the local authorities lacked experience regarding the hydrogen and the fuel cell homologation aspects. They showed a serious interest in the HYCHAIN vehicles and the hydrogen fuel cell technology. All the representatives involved were enthusiastic and supportive to define the requirements. In some cases, the authorities relied on the expertise of a third party, such as certified laboratory. We can safely say today that thanks to this process, homologation of hydrogen and fuel cell vehicles has moved a step forward in all the four HYCHAIN countries since the local authorities have considerably increased their knowledge.

Today all the deployed vehicles are certified or homologated (with the exception of the utility vehicle for France). This achievement was a key project milestone as it allowed for the deployment of the HYCHAIN vehicles, their operation and the associated demonstration tasks (training, data gathering, support, dissemination)

## 3 Commercial Challenges

The commercial experience of HYCHAIN provides a valuable feedback to position hydrogen as an energy carrier in new market segments for sustainable development and to test the commercial acceptance of this technology. The HYCHAIN vehicles were mainly targeted – for infrastructure reasons - to the customers with the capacity to deploy captive fleets (municipalities or private company). There are many advantages: maintenance is local;

technical support and training are offered to identified users and the hydrogen supply chain is centralized and controlled.

Several business models were studied and tested with the targeted customers. Most of the discussions with the customers were focused on the price of the vehicles in comparison with a standard combustion engine version (CAPEX) and the associated energy cost (OPEX), leveraged with the ecological image and the HYCHAIN communication package.

The HYCHAIN offer had many positive aspects.

- Most of the products fit well the targeted customer needs: a medium size passenger transportation vehicle (Midibus), a light duty vehicle (utility vehicle) and a small size duty vehicle (Cargobike) for “last mile” type of urban transport.
- Environmental benefit of using an electrical vehicle powered by a hydrogen fuel cell
- Technological benefits (increased driving range and reduced recharge time) compared to standard battery electrical vehicle.
- Wide exposure for the customers through HYCHAIN, around a demonstration project of high visibility and around an innovative technology.

Yet, the commercial objectives turned out to be very challenging; only 50 vehicles were sold compared to the initial target of 158. There are several reasons to this situation, some are structural, and others are HYCHAIN specific.

The main blocking factor was the cost of buying and operating the vehicles. The customers have all the figures in hand to compare with standard combustion vehicles of their own fleet. In some business cases, the calculated cost of ownership reached three times the standard ownership level of a diesel powered vehicle.

Another interesting point was related to the hydrogen local storage. In some cases, the premises were not suited to receive hydrogen or to maintain fuel cell vehicles, and the necessary investments (ventilation, H2 detectors, separate compounds…) were viewed as too costly by the customer.

Finally, the commercial challenge for the HYCHAIN partners was inherent to the delay in the development and the homologation of some vehicles. In most cases, the vehicles were not available for a test by the customer. Selling innovative vehicles via a presentation helps generate interest in the mind of the prospective customer. But it is not sufficient to finalize the sale when the discussion falls down to the price review. Being able to show the vehicle in its operational environment would have certainly improved the sales figures. The main lesson that we learned is that the market is not ready to pay substantial premium for new “green” technology. The need for state aids remains very strong.

## 4 Public Acceptance and Products

The public acceptance and the targeted groups’ acceptance were always very good. There is a real interest in an innovative environmental alternative fuel. With the first deployed vehicles (24), we are already starting to get operational feedback. The HYCHAIN partners set up many tools to monitor the performance and to assess the acceptance of the hydrogen fuel cell technology. However at the start of deployment phase, the utilization ratio was not ramping up as quickly as we expected. There is a first lesson to be drawn from this observation. Some vehicles, mainly the wheelchair and secondly the Cargobike, were not well positioned and lacked end users willing to operate them. This highlighted the importance to have products which are well adapted to the end users. Products which target a large base of users and can be operated in all kind of circumstances.

We also learned that the users need extensive and close accompaniment by the HYCHAIN partners to overcome reliability issues that are normally encountered and expected in a demonstration project of this kind in order to build trust in the technology. Accompaniment turned out to be essential as the customer's expectations can be very high. They expect to be able to use the vehicle as a normal vehicle with equivalent performance. This was the case in Soria, for instance. In Germany, the expectations were more in line with the reality of the products. This is probably due to the fact that German customers are already participating in H2 developments (e.g. Herten).

## 5 Managing a Long and Complex Project with 24 Partners

The management of HYCHAIN is clearly a success story thanks to the structure that was adopted. The management is centralized in an executive board of four people where each of the members represents one of the four involved regions. The local and centralized management has contributed to steer without conflict and overcome successfully the difficulties encountered during the project execution with the agreement of all the partners. The collaborative relationship between the local regional representative, the HYCHAIN partners and the political organizations contributed efficiently to the successful implementation of the project in each region.

## 6 Conclusion

HYCHAIN MINI TRANS has already achieved one of its most significant objectives. From its first feedback, we are able to draw many valuable lessons for the implementation of hydrogen and fuel cell technology. It shall continue to do so, as more vehicles are used for longer time. HYCHAIN is paving the way for future projects.

With the precious inputs, it gives sound economical models related to the Hydrogen fuel cell technologies and their implementation in the transportation domain. The HYCHAIN experience has clearly proven to be one of the cornerstones to launch this new technology.

HYCHAIN MINI TRANS has involved more than 200 staff who will be able to capitalize on their experience. Definitely, there is room for improvement of the products and there are many opportunities to reduce the cost structure for Hydrogen and fuel cells. However, it is obvious that larger volumes of vehicles are needed to achieve the critical mass and allow standardization and cost reduction

**Project partners**

Hychain partners are Air Liquide SA, AXANE, BESEL, WIN, Air Liquide Italia, CEA, INERIS, INPG, PAXITECH, ASCOPARG, Air Liquide España, CIEMAT, DERBI, RUCKER, CEU, DOMENECH, IBERDROLA, WI, HYDROGENICS, MASTERFLEX, FAST, VEM, DEMOCENTER, Air Liquide Deutschland

# Collaboration in a Local Hydrogen Cluster in Germany

**Boris Jermer***, HyCologne, Hydrogen Region Rhineland, Germany

According to Michael Porter [1] a Cluster "is a geographically proximate group of interconnected companies and associated institutions in a particular field, linked by commonalities and complementarities". As the sum of its parts is of greater value than each individual company or institution (e.g. clusters create synergy). As Feldman [2] points out cluster formation is a process that relies on the coevolution of technology, business models and local supporting institutions.

Clusters have the potential to improve competitiveness (which results in improved productivity) in three ways: (1) they improve productivity through improved access to specialized suppliers, skills and information. (2) Innovation is given more importance as the need for improvement in processes of production is highlighted and (3) once established, clusters tend to grow as a result of the creation of new firms and the entrance of new suppliers.

## 1 Approach and Members of HyCologne

HyCologne is a regional hydrogen and fuel cell cluster in the Rhine area around Cologne. They work to establish hydrogen as an energy carrier in and around Cologne. Within its members HyCologne organizes meetings to network organizations relevant to hydrogen as an energy carrier. They are involved in international fairs and events relevant to hydrogen and activities for public awareness for hydrogen technology. This includes developing hydrogen safety programs, general public education programs, and fire department training programs. The following Organizations are members of the formalized Cluster HyCologne [3]:

1. ChemCologne e.V. » Chemical Cluster in the Cologne Area
2. CK Standortentwicklung » Regional Consulting Company
3. CHEMPARK » Service provider for the Leverkusen Chemical Park
4. DLR e.V. » Research Institute
5. Energy Hills » Energy-Cluster in the Euregio (Aachen, Heerlen, Maastricht)
6. Fachhochschule Köln » Cologne School of Applied Sciences
7. IHK Köln » Cologne Chamber of Commerce
8. InfraServ GmbH & Co. Knapsack KG » Service Provider for Chemical Park Hürth
9. NOVALINK » Technology consulting firm
10. Praxair Deutschland GmbH » Worldwide provider of industrial gases
11. Regionalverkehr Köln GmbH » Regional Transport Agency Cologne
12. Rhein-Erft-Kreis » District around Cologne

* Corresponding author, email: jermer@hycologne.de

13. ST@RT HÜRTH GmbH » Technology and Start-Up Centre
14. Stadt Brühl » City of Brühl
15. Stadt Hürth » City of Hürth
16. Stadt Köln » City of Cologne
17. Stadtwerke Brühl GmbH » Public utilities Brühl, service provider
18. Stadtwerke Hürth AöR » Public utilities, Hürth, service provider
19. TÜV Rheinland » Safety and Certification
20. Wirtschaftsförderung Rhein-Erft GmbH » Local Agency for Economic Developme the definition of cluster types (Porter 1999) HyCologne can be understood as nt

According to a horizontal cluster as different public and private organizations are sharing resources and are managing knowledge centrally and formalized. This knowledge is brought together by two cluster managers and is used to (1) initiate new projects, (2) share technological risk and (3) enable interorganizational learning.

## 2 The Main Tasks of the Cluster

HyCologne is organized as a Public Private Partnership and consists of currently 20 members who facilitate the commercialization of hydrogen energy technology in the area of Cologne. HyCologne is following four main tasks: (1) Strengthen the strong cluster with other universities, public partners and private stakeholders (2) Using the existing resource of waste-hydrogen from the local chemical industry [4] and expanding the existing hydrogen infrastructure (pipeline network) (3) Operation of a hydrogen bus fleet vehicles including filling stations and infrastructure [5] (4) Establishment of fuel cell power plants for industrial electricity and heat generation (CHP).

With its 20 members HyCologne is working on networking among its members for relevant projects. They also help by raising capital and finding third party funding for projects. Current projects include: Development of a hydrogen infrastructure for hydrogen fuelled buses and hydrogen fuelling stations utilizing the waste hydrogen from the local chemical industry. The initial refuelling station and two buses are planned to be operational in 2010. Other projects include: Stationary Combined Heat and Power (CHP) fuel cell power plant units for energy production to utilize the hydrogen waste stream from the seven sodium chloride electrolyzing plants around Cologne, mobile and portable fuel cell systems, turbine- and power plant technology, hydrogen infrastructure and logistics and consulting services for public and private organizations

## 3 A Bottom-up Hydrogen Cluster

HyCologne is one of the few independent hydrogen clusters in Germany. There is no direct funding to the cluster like many other networks (Energy Agency NRW, Hessia Agency, etc.) HyCologne understands itself as an entrepreneur driven cluster that is “bottom up”, meaning that private organizations networked among themselves to form HyCologne instead of being a state initiated venture and remains a neutral position when consulting among its members. There is great scope for utilizing hydrogen in a number of stationary and transport projects. These include building a fuel cell power plant and the setup of a fleet of hydrogen buses and other vehicles which will be operated on regular service in cologne and the surrounding area. HyCologne collaborates with a number of manufacturers, other clusters and cities around the world to not only achieve this goal technically but also run the fleet on an economic viable basis. The hydrogen cluster can provide valuable knowledge transfer and project collaboration regarding management of hydrogen as a fuel.

Little is known how clusters come into being [6]. Anecdotal stories suggest that successful clusters start themselves but there is little evidence that it is possible to proactively start a successful cluster. Evidence from those who have tried to start clusters is just that – it is very difficult.

## 4 Cluster Genesis and History of the Cluster

There are other factors that are helpful in the genesis of a technology cluster. A link to a university provides and research institutes brings in an increased flow of ideas, adds to the pool of individuals who may become entrepreneurs and is a key mechanism for developing a science park. This has been done in 2006 with DLR and in 2008 when the Cologne School of applied Sciences became members of HyCologne. The existing hydrogen infrastructure (pipeline in the chemical park) turned out to be hard to access as the use and mode of operation is interconnected with other processes which are rather sensitive.

The establishment of HyCologne took around five years to become noticeable and a will probably need another five years to become a major entity. One of the key factors for any new cluster seems to be the importance of entrepreneurship as an endogenous process. Entrepreneurs provide encouragement and their successes persuade others to follow their ideas. These individuals also bring initial funding with them to allow a first organization of the cluster which creates to returns and binds a lot of resources (e.g. time and money).

HyCologne goes back to the “Interest Group for Hydrogen (IGH2)” which has been initiated in 2004 by a local start-up-centre (START Hürth), an industrial service provider (Infraserv Knapsack) and a small technology consulting company (Operathing). After having understood that big resources of hydrogen are available in the chemical park and could be used for infrastructure projects in the Cologne-Area the initiators hired a network agent to further examine the local situation and win more partners in the region. After a period of learning and listening to local companies, there where other partners joining the network paying some money to further establish a central management and administration office. The strategy of the state founded “Energy Agency NRW” [7] was focussing on the field of “special applications” (e.g. bikes, UPS, small applications) and thus had little share with the large technological systems approach [8] of HyCologne. Since the beginning IGH2 and later HyCologne have been focussing on large scale technologies like public transport, busses, fuelling stations and power plants. Give the fact that NRW is the biggest federal state in Germany with a high and dense population the government of NRW has started to accept this reasonable strategy since 2008 and now also begins to initiate large scale projects in the transport sector. In early 2007, HyCologne was formally founded by seven members as a public private partnership (e.V. [German: eingetragener Verein]). Soon after the formal founding the number of members increased rapidly and new partners were willing to join the cluster.

## 5 Results and Outlook

Now in May 2010 there are 20 partners forming a rather strong backbone for local hydrogen energy projects in the Cologne area all willing to support new projects with hydrogen as an energy carrier. The coming years will show whether HyCologne is able to contribute to the initial stage of a hydrogen infrastructure in Germany through giving specific examples and demonstrations how hydrogen related projects can be successfully realized on a local level.

## References

[1] Porter, M.E. (2000) Location, Clusters, and Company Strategy Oxford: Oxford University Press

[2] Feldman, M. P. (2001) The entrepreneurial event revisited: firm formation in a regional context, Industrial and Corporate Change 10, 861–891.

[3] http://www.hycologne.com, (Accessed in March 2010)

[4] Maisonnier, G., Perrin, J., Steinberger-Wilckens, R., and Trümper, S.C. (2007) European Hydrogen Infrastructure Atlas and Industrial Excess Hydrogen Analysis, Oldenburg

[5] http://hycologne.de/wasserstoff-tankstelle-in-huerth-eroeffnet-chemergy.phtml (Accessed in March 2010)

[6] Braunerhjelm, P., Feldman, M.P. (2005) Cluster genesis: technology-based industrial development, Oxford Univsersity Press

[7] www.brennstoffzelle-nrw.de (Accessed in March 2010)

[8] Edited with Renate Mayntz. (1988) The Development of Large Technical Systems. Frankfurt am Main: Boulder, CO: Campus Verlag; Westview Press

# The HyRREG Project: A Roadmap for SUDOE

**Esther Chacón**, **Loreto Pazos**, Instituto Nacional de Técnica Aeroespacial (INTA), Madrid, Spain
**Rei Fernandes, Rui Pimenta,** Instituto Superior Técnico (IST) Lisboa, Portugal

## 1 Introduction

The HYRREG project is an initiative funded by the European Commission through the IVB program of cooperation of the territorial area of southwest Europe (SUDOE). The two main objectives are: to develop a platform for generating hydrogen related projects and to define a roadmap with the aim of enhancing the competitiveness and development of industry in the fields of hydrogen and fuel cell technologies in the SUDOE area.

The idea of developing a specific roadmap for SUDOE has its origin in the HyWays project. HyWays was an integrated project co-funded by research institutes, industry and the European Commission under the 6$^{th}$ framework programme that carried out a road mapping exercise to integrate hydrogen technologies into the European energy system. HyWays used a 'hybrid' methodology: it integrated extensive quantitative computational modelling as well as qualitative components such as actor analysis, conducted through the KCAM methodology [1, 2], and stakeholders preferences for the validation process (see figure 2).

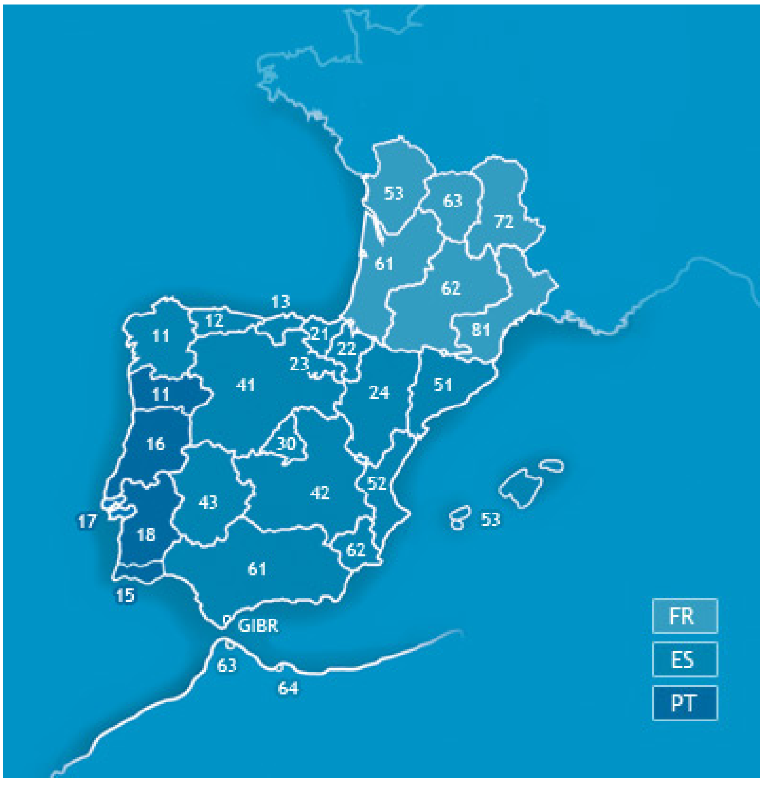



**Figure 1: SUDOE regions.**

France and Spain took part in the HyWays project and as a result a general analysis of hydrogen deployment in these countries was generated. However, some generalities and assumptions used in the HyWays analysis are not the most appropriate for the SUDOE reality. In addition, there has been a demand from stakeholders participating in HyWays to analyse the SUDOE area thoroughly by regions. In this sense, France has already finished their national roadmap in the project HyFrance and the HiPo project has made progress towards a national roadmap in Portugal. There is now a need for SUDOE to launch a specific hydrogen roadmap for the region.

## 2 Methodology

The HYRREG project is focused on the SUDOE Region (Southwest Europe) which is comprised of 30 regions and autonomous cities representing about 770 120 $km^2$ (18.2% area of EU-27) and 61.3 m inhabitants (12.4% of EU-27).

SUDOE features related to energy are easily distinguishable from the rest of Europe and that is why it is necessary to create a specific hydrogen roadmap for this area. In contrast to the HyWays methodology, the HYRREG analysis is mainly qualitative. Both stakeholders preferences and country specific conditions such as availability of resources and environmental policies as well as the characteristics of the current and future energy system, are taken into account.

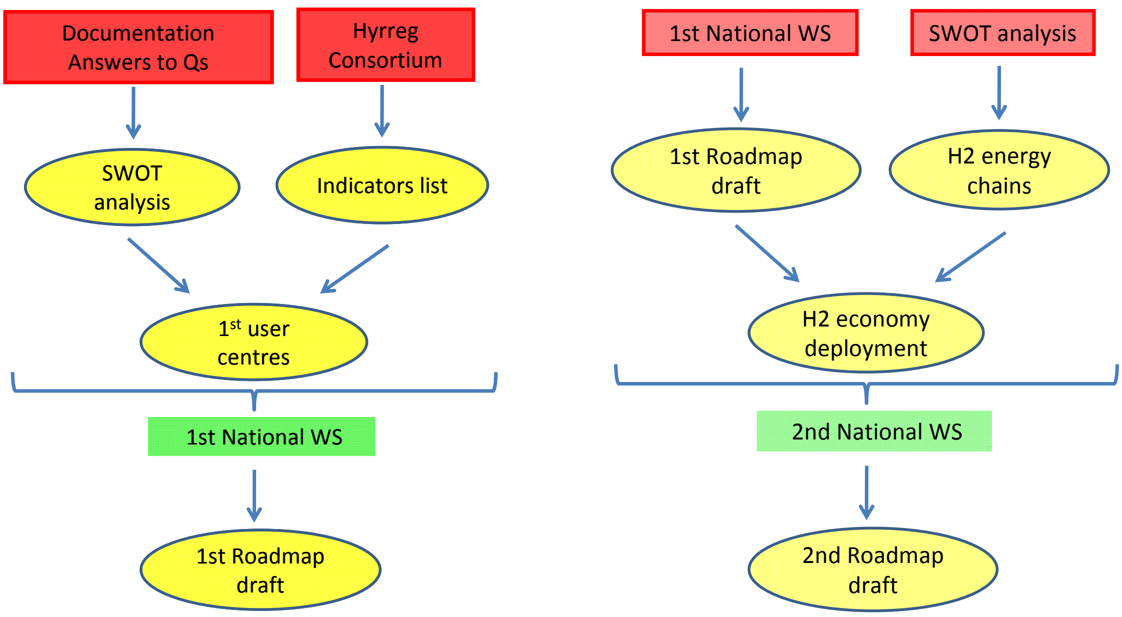



**Figure 2: Methodology.**

The methodology used in the HYRREG roadmap is mainly based on an iterative enquiry process to a selected stakeholders group involved in general in energy context.

In order to define the starting scenario for a hydrogen economy a series of questionnaires (Qs) was prepared. Each questionnaire was devoted to one aspect of the hydrogen energy chain: production, storage/distribution, conversion/final use and perception/promotion. These questionnaires were addressed to the relevant regional actors: the stakeholders. Industry, public institutions and decision makers were included in the HYRREG database and asked to collaborate by filling in the questionnaires. A first analysis of SUDOE was made using available documentation and stakeholders´ answers to Qs. As a result, SWOT (Strength, Weaknesses, Opportunities and Threats) analysis of each region regarding hydrogen economy implementation was carried out.

Based on a list of indicators defined by the Spanish Technological Hydrogen and Fuel Cells Platform [3], the project consortium defined the indicators that would identify the first user centres of hydrogen in SUDOE, i.e., the most promising regions regarding the implementation of a hydrogen economy in each of the three countries participating in HYRREG. Subject to stakeholders´ validation, they will be the seed for the hydrogen roadmap.

Once SWOT analysis was made and selection of first user centres was addressed, hydrogen energy chains for each of the first user centres will be identified.

## 3 Actor Analysis: KCAM

The “Key Changes and Actor Mapping” (KCAM) is part of a process of Actor Analysis, which constitutes a source of largely qualitative information, providing valuable information to stakeholders for use and consideration in the construction of the hydrogen energy roadmap. The aim of the KCAM methodology is to examine qualitative concerns in a structured way, seeking to systematically examine each component of each hydrogen chain selected by stakeholders.

For the purposes of Actor Analysis a “Key Change” may be defined as:

“One of a number of distinct changes that are foreseen as necessary to progress from the current energy system to the end-vision as described in each hydrogen chain selected”.

The KCAM methodology differentiates between two kinds of key changes:

- Generic Key Changes – which apply to all regions. They describe the ambient conditions which are true in all instances. They are therefore predominantly related to basic technological parameters. Generic Key Change descriptions have to be validated by an industry-based committee.
- Member State Specific Key Changes – which are applicable only within the confines of each specific region. They apply specifically to the region in question and avoid describing key changes which are more widely applicable such as the technological status of hydrogen technologies. They are related to region specific energy supply and demand trends, energy transportation infrastructure, political disposition and policies, and national societal knowledge and technology acceptance levels. Region specific key changes are validated by representatives and stakeholders from each region following preliminary mapping work by the project team.

Actor Analysis will culminate in an Actor Analysis Report, which presents the methodology as well as Key Change Difficulty Summary Charts and Broad Actor Group Heat Charts, as well as cross-cutting analyses. [2, 4]

## 4 Roadmap Evolution

As in the HyWays project, HYRREG involves the stakeholders right from the start of the project and integrates their preferences and opinions, making it different from other roadmapping exercises. The stakeholder validation process is present throughout the whole study, at the beginning by consulting them with questionnaires and during the process at workshops where all the steps of the roadmap are discussed.

HYRREG´s deployment infrastructure for a hydrogen economy will be established for three timeframes: short term (2020), midterm (2030) and long term (2050). First user centres are expected to occur in the short term and, based on natural resources, state of the art and all aspects reflected in the SWOT analysis, first hydrogen energy chains will be selected.

But technological, political, economic and social aspects will lead to a different evolution of this first scenario. Technological advances, mass-production, economy of scale, environmental policy and social acceptance have to be taken into account when defining the future energy system and in consequence, the future scenario for hydrogen.

The evolution of a hydrogen economy from 2020 to 2050 will be defined in the WS taking into account European and Worldwide previous commitments such as the Kyoto protocol, the European Hydrogen and Fuel Cell Technology Platform guidelines, National initiatives, etc.

**Table 1: Roadmap evolution.**

| STEP | ACTION | WHO | SOURCE | Comments |
|---|---|---|---|---|
| 1 | SWOT Analysis per region | INTA<br>Stakeholders | Documentation<br>Questionnaires | |
| 2 | Indicators list selection | HYRREG partners | Documentation<br>Opinions | |
| 3 | FIRST user centres selection | Stakeholders | Indicators list | At workshops |
| 4 | Hydrogen energy chains selection for first user centres | Stakeholders | SWOT analysis | At workshops |
| 5 | KCAM* analysis | Stakeholders/<br>HYRREG partners | Hydrogen energy chains | At workshops |
| 6 | Infrastructure development vision | Stakeholders | Opinions | At workshops |
| 7 | Challenges<br>Recommendations | Stakeholders | Opinions | At workshops |

* Key changes and actors mapping

### References

[1] HyWays (2009) "The European Hydrogen Roadmap", http://www.hyways.de, accessed 2nd March 2010.

[2] Hugh, MJ, Roche, MY, Bennett, SJ (2007) "A structured and qualitative systems approach to analysing hydrogen transitions: Key changes and actor mapping", *International Journal of Hydrogen Energy*, Vol. 32 (10-11) 1314 – 1323.

[3] Abilities Analysis Group of the Spanish Technological Hydrogen and Fuel Cells Platform (2009). “Priorization report for the criteria of first user centres selection”.

[4] Seymour, EH, Murray, L, Fernandes, R (2008) Key Challenges to the introduction of hydrogen—European stakeholder views, *International Journal of Hydrogen Energy*, Vol. 33 (12) 3015 – 3020

SA Strategic Analyses

SA.1 Research & Development Targets and Priorities

SA.2 Life-Cycle Assessment and Economic Impact

SA.3 Socio-Economic Studies

SA.4 Education and Public Awareness

SA.5 Market Introduction

SA.7 Regional Activities

SA.8 The Zero Regio Project

# Zero Regio: Recent Experience with Hydrogen Vehicles and Refueling Infrastructure

Heinrich Lienkamp and Ashok Rastogi

**Abstract**

The project Zero Regio, co-financed by the European Commission within the 6th Framework Program, aims at demonstrating hydrogen infrastructure and fuel cell passenger vehicles in European cities. Demonstration activities have taken place in Germany and Italy. Hydrogen from two different sources – chemical by-product in Germany and natural gas reforming in Italy – was employed in fleet demonstration. Five Mercedes-Benz A-Class F-CELL vehicles, including one vehicle with 700 bar storage, have been tested in Frankfurt and three fuel cell vehicles (Panda) from Fiat have been demonstrated in Italy. Both fleets have gone through real-life driving cycles over a long period (3 years ending in November 2009). Experience with this demonstration is presented. Evaluation of data collected and analyzed during the demonstration is presented, providing important information on the performance, availability, maintenance requirements, and consumption of the FCVs tested in comparison with conventional vehicles. Some socioeconomic aspects of the fleet demonstration and the dissemination activities are also presented. Experience with refueling the FCVs is presented. At both sites, Frankfurt in Germany and Mantova in Italy, public multi-energy service stations have been built within the project. Significant characteristics of hydrogen infrastructure at these stations, such as high-pressure pipeline transport, on site production, compression schemes, precooling of hydrogen, dispenser designs, and communication between vehicle and dispenser, with regard to refueling of compressed hydrogen (at 350 and 700 bar) is briefly described. Based on the demonstration experience, areas in both fuel cell vehicles and hydrogen infrastructure where further development is necessary are highlighted. Future developments regarding the filling station and the growing demand for hydrogen and filling stations are also discussed.

# SI Safety Issues


| | |
|---|---|
| SI.1 | Vehicle and Infrastructural Safety |
| SI.2 | Regulations, Codes, Standards and Test Methods |

# Safety Analysis of Hydrogen Vehicles and Infrastructure

Thomas Jordan and Wolfgang Breitung

**Abstract**

This chapter summarizes the state-of-the-art related to safety analysis of hydrogen vehicles and infrastructure. Many aspects have been treated in more detail in the reports of the European Commission-supported HySafe Network (www.hysafe.net). The potential use of hydrogen as an energy carrier and in particular its application as a fuel in vehicles require new operational parameters which are very different from those currently used in the chemical and petrochemical industries. This is why the industrial experience gained so far is applicable only partially. Safety analyses require the definition of acceptable risk levels, which are implicitly or explicitly contained in standards or regulations or might be derived from established technologies. A quantitative measure of risk is the product of a probabilistic factor representing the frequency of occurrence of hazardous events and of the associated damage. As these frequencies of failures are largely unknown and difficult to predict, it is recommended to focus on the deterministic evaluation of the damage and of the effectiveness of mitigation measures. For the deterministic consequences, evaluation of the distribution, ignition, and combustion phenomena are the key elements of the event sequence. The distribution of hydrogen is well understood as long as phase transition or near-critical conditions might be excluded. The latter phenomena are linked mainly to liquid hydrogen applications. The knowledge and modeling capabilities regarding the ignition phenomena are still incomplete. The classification of ignition sources into weak and strong igniters and the degree of conservatism related to assumptions about timing and location are still under development. Transitional behavior of flames plays an important role. The principal mechanisms are well captured, but the transfer to real accidental scenarios and the new physical domains is not yet accomplished. Commonly agreed, harmonized performance-based standardization on an international level relies on an appropriate understanding of the relevant mechanisms. This understanding will be further developed by internationally coordinated pre-normative research.

# Safety Distances for Hydrogen Refuelling Station

**Angunn Engebø**, DNV, Norway
**F. Barth**, AL, France
**F. Markert**, DTU, Denmark
**P. Middha**, GexCon
**M. Wardman**, HSL
**J. Chaineaux**, INERIS
**D. Sebarnescu**, EC/DG-ENER
**D. Baraldi**, EC/DG-JRC
**S. Nilsen**, Statoil
**A.V. Tchouvelev**, A.V. Tchouvelev & Associates Inc.
**N. Versloot**, TNO
**A. Marangon**, UNIPI

Safety distances are widely used for preventing incidents caused by unintended interference between two activities or for preventing harmful consequences from an incident to objects or people in the vicinity. EIGA [1] has expressed this as: *"Safety distances need to be considered as a generic means for mitigating the effect of a foreseeable incident and preventing a minor incident escalating into a larger incident."* Some countries have specific regulations, expressing required distances based on standard equipment, while others also allow a performance based approach using guidelines or codes on how to determine safety distances. For hydrogen equipment, specific requirements for safety or separation distances are being established for Gaseous Hydrogen refuelling stations e.g. in NFPA 55: 2010 [2], in 2003 International Fire Code [3] as well as in the ISO TS 20100: 2008 [4]. There is also ongoing work on safety distances within ISO/TC197/WG11.

The challenge is to provide an approach allowing to standardize installation requirements in order to facilitate the deployment of a fuelling station infrastructure, while allowing for non standard designs and adaptation to technological progress. This paper discusses the approaches implemented in the different standards and also compares the approaches to that of the European Gas Industry Group (EIGA) guideline [1]. The EIGA safety distance procedure has been applied to a hydrogen refuelling station (Figure 1) designed by HySafe participants, to avoiding confidentiality issues. The results and recommendations are obtained from comparison and discussion of the results. The work was done by the Risk Assessment work package in the EU 6$^{th}$ FP HySafe NoE (HySafe).

Safety distances are determined using different methodologies. An example is the concept of consequence lengths that determines the impacts of releases and fires up to a certain harm criteria, which represents a deterministic approach. Another approach is being used in QRA where the safety distance is determined using the Individual risk (IR) and/or societal risk criteria (SRC). For determination the frequency of each failure is multiplied with the probability of a certain consequence depending on the distance to the incident location. All products are summed to give the overall individual risk as a function of distance, that is the risk to an unprotected person placed permanently a certain distance from the accident source. The SRC is basically the same approach, but is also regarding the population density around the object of concern.

The EIGA methodology is comparable to the described for QRA. The main difference is the initial exclusion of incidents of very low frequency. The EIGA guideline uses a per incident acceptance threshold criterion of Ft < $3.5 \times 10^{-5}$ per annum; for each potential hazardous event the frequency shall not exceed $3.5 \times 10^{-5}$ per annum. For events with a higher frequency, safety distances must be established. This means that for each event the tolerance criterion applied in the EIGA guideline is

- $3.5 \times 10^{-8}$ fatalities per annum
- $3.5 \times 10^{-7}$ cases of considerable material damage per annum

The European guideline for risk based safety distances for land use planning [5] suggests an acceptance criterion for individual risk of $10^{-5}$, with an ALARA (As Low As Reasonably Achievable) region between $10^{-6}$ and $10^{-5}$. The IEA HIA Task 19 Hydrogen Safety has suggested similar criteria for hydrogen infrastructure [6]: Individual risk < $10^{-5}$, with an ALARA region between $10^{-7}$ and $10^{-5}$.

In comparison, the EIGA guideline criterion appears to be more strict, but as the contribution from major accidents with a frequency less than $3.5 \times 10^{-5}$ is not included, the criterion can be said to be line with generally accepted levels for tolerable risk.

”Harm" and "no harm" criteria for fire and explosions proposed for calculations of safety distances in the guideline are given in the table below.

**Table 1: Criteria for fire and explosions.**

| **Hazard** | **target** | **“no harm” criterion**<br>events likely during lifetime | **“harm” criterion**<br>events not likely during lifetime |
|---|---|---|---|
| Fire | people | 1.6 kW/m$^2$ | 9.5 kW/m$^2$ (sustained fire) |
| Fire | equipment | | 37.5 kW/m$^2$ |
| flash fire | | ½ LFL | LFL |
| explosion | people | 2 kPa | 7 kPa |
| explosion | equipment | | 20 kPa |

The “no harm” criteria are rather strict: The radiation criterion (1.6 kW/m$^2$) which is comparable to solar radiation on a bright day and is the level defined as acceptable maximum for continuous exposure (from a flare) in API 521 [7]. The explosion criterion is far below what is reported as harmful for humans, except for secondary effects from broken glass. In this study the criteria are applied as recommend though.

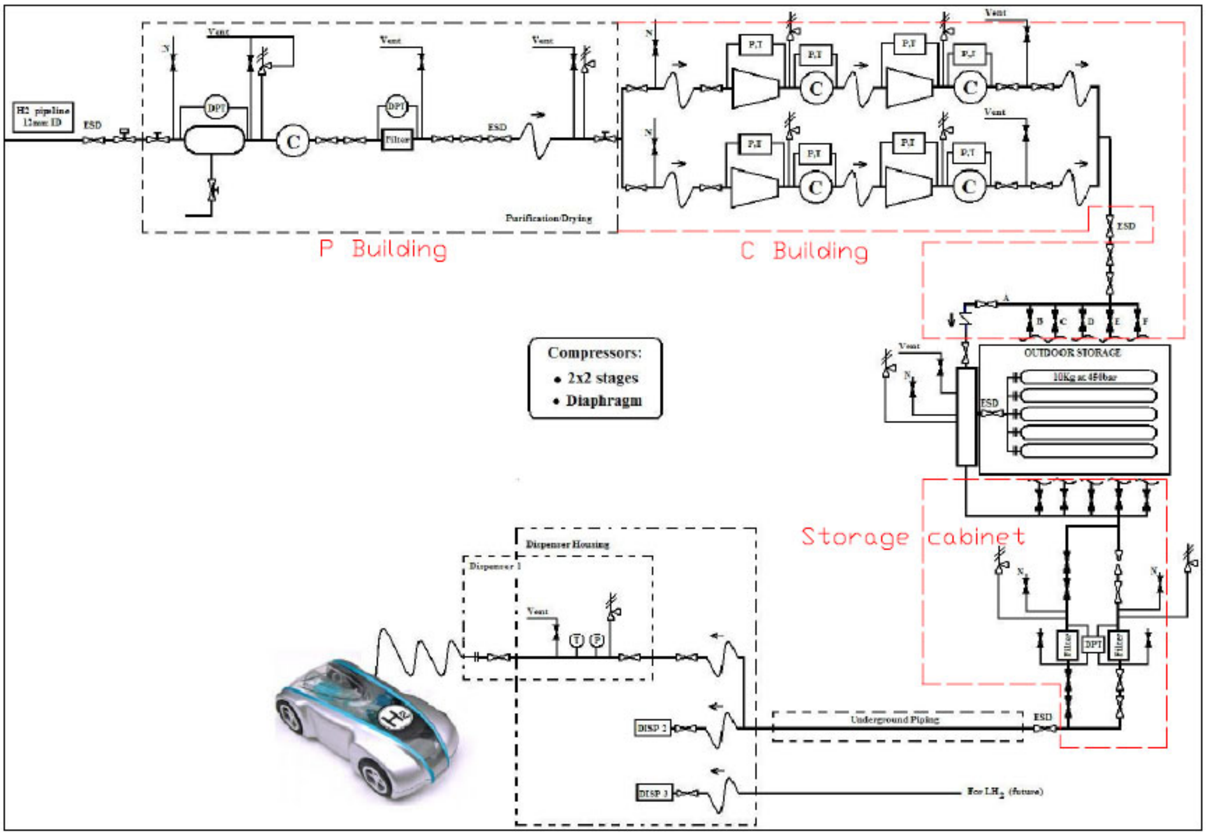



**Figure 1: Hydrogen refuelling station evaluated.**

In total more than 50 hazards were identified. For most of these risk reducing measures are already recommended practice: E.g. for ventilation failure for the hydrogen compressor building: The control system will shut down the container (compressor and all electrical equipment inside the container) in case of ventilation failure (or failure of air flow confirmation signal). In addition, the safety system will give an alarm if hydrogen is detected at 10 % of flammable level shut down the container at 25 %. The frequency of a ventilation failure causing a potentially harmful effect was thus evaluated as well below 3.5 x $10^{-5}$.

Safety distances were done for the scenarios listed:

**Scenario 1A**: Small leak in outside storage bank valves. Leak, and if ignited, exposure of storage bottles. A total content of 50 kg (5 tanks 10 kg each) of hydrogen means this could lead to a fire of very long duration. The leak is modelled in PHAST [8] as a 0.5 mm hole size, which will give a leak of 4.4 g/s and a jet fire length of 1.3 meters. The modelled range of radiation above 1.6 kW/m2 (no harm) is similar to the range of the jet. Within the jet flame envelope the temperature will be sufficient to cause damage to exposed equipment as well as harm to people.

**Scenario 1B**: Escalation of 1A by tension cracks and possibly rupture of exposed bottle(s). Release of content of one storage bank and immediate ignition of release. Atex (zone 2) classification of equipment will reduce (but not eliminate) ignition probability. This event (rupture of exposed bottle) is evaluated as not likely to occur during the lifetime of the project, and the safety distance is thus calculated for “harm” criteria: radiation of 9.5 kW/$m^3$ for people and 37.5 kW/$m^3$ for equipment.

Each storage bank consisting of 5  10 kg bottles connected with 8 mm pipes. Modelling the release in PHAST [8] gives a leak rate of 1 kg/s and a maximum jet fire length of 15 meters, which also is the range of radiation levels above 37.5 kW/$m^3$. Radiation above 9.5 kW/$m^3$ has a range of 20 meters.

Preventing scenario 1A from escalating into scenario 1B cannot be achieved by increasing the distance. One will thus either have to implement measures to reduce the frequency of scenario 1B below the Ft or base the safety distancing on scenario 1B.

**Scenario 2**: GH2 leakage, most likely caused by vehicle drive away. Safeguards: Flow restriction in filling line, limiting the flow to 6 grams per second and EXV valve (flow actuated normally open shut off valve) close to dispenser. Modelling the release in PHAST gives a jet fire length of 1.5 meters for an ignited leak and the estimated maximum extent of a flash fire (distance to ½ LEL) of 5 meters. The EXV will limit the duration of the leak and the probability of a delayed ignition and a flash fire. For a jet fire the “no harm” safety distance should thus be set to 1.5 meters. For the less likely event of a flash fire the “harm” criterion may be applied – which gives a distance of 3 meters.

**Scenario 3**: Refuelling started with (undetected) minor leak. Pressure drop too small for EXV valve to close (assumed leak rate of 10 % of maximum filling rate). Flow restriction will work. Modelling the release in PHAST gives a jet fire length of 0.5 meters for an ignited leak and an estimated maximum extent of a flash fire of 2 meters.

**Scenario 4**: GH2 leak inside compressor enclosure. Small quantity of hydrogen within process equipment. Release rate will decay immediately after detection and shutdown. Safeguards: Gas detection, alarm, automatic shut down if 0.25 LEL or ventilation failure. Relief panels opening at 0.1 bar overpressure. Frequency for an overpressure exceeding 0.1 bar is less than 3.5 x $10^{-5}$. Utilising the Multi Energy Method [9] this gives a resulting overpressure below 7 kPa (harm criterion) at 6 meters distance.

The distances are compared to recommended distances from the HyApproval [10] project in the table below.

**Table 2: Comparison of safety distance with HyApproval distance.**

| Case | Frequency | Effect | Criterion | Safety distance | HyApproval distance |
|---|---|---|---|---|---|
| 1A | Likely | jet fire | no harm | 1.3 m | |
| 1B | < proj. life | jet fire | harm | 20 m (people)<br>15 m (material) | “L2 large jet”<br>21 m |
| 2 | likely | jet fire | no harm | 1.5 m | - |
| 2 | unlikely | flash fire | harm | 3 m | 6 m |
| 3 | likely | jet fire | no harm | 0.5 m | - |
| 3 | likely | flash fire | no harm | 2 m | - |
| 4 | unlikely | Explosion | harm | 6 m | 6 m |

The seen variations in calculated distances are related to different hole size and to different operational pressures.

Comparing the distances to separation distances or “setback” distances in different fire codes is done in the table below.

**Table 3: Comparison of the distances to separation distances.**

<table>
<tr><th>Case</th><th>Safety distance</th><th>ISO/TS 20100 [4]<br>V>10 000 l</th><th>International Fire Code[3](V<120m³)</th><th>NFPA 55 [2]</th></tr>
<tr><td>1A</td><td>1.3 m</td><td rowspan="2">4 m to sidewalk<br>8 m to public area<br>6 m (combustible)</td><td>1.5 m</td><td rowspan="2">0 m (workers)<br>4.6 m (public/cust.)<br>3 m (equipment)</td></tr>
<tr><td>1B</td><td>20 m (people)<br>15 m (material)</td><td>1.5 m</td></tr>
<tr><td></td><td></td><td>P<=45 MPa</td><td></td><td></td></tr>
<tr><td>2</td><td>3 m</td><td>3m (sidewalk)<br>4m (public area)</td><td>0</td><td>0</td></tr>
<tr><td>3</td><td>2 m</td><td>3m (sidewalk)<br>4m (public area)</td><td>0</td><td>0</td></tr>
<tr><td>4</td><td>6 m</td><td>3m (sidewalk)<br>4m (public area)</td><td>0</td><td>0</td></tr>
</table>

All the codes reviewed recommends distances for storage of hydrogen. ISO TS 20100 [4] also give recommendations for filling, but the options for taking safeguards into account is limited; this is demonstrated clearly by Case 1A/1B.

The determination of frequencies and the modelling of the resulting consequences involve a degree of uncertainty that will influence the resulting safety distances. This has been addressed in the ASSURANCE project [11]. E. g. for an ammonia plant the predicted radius at IR = $10^{-6}$ per year ranged from 820 to 1325 m. It was found that the determination of frequencies was considerable more uncertain than the results of the modelled consequences. In practice and especially for the new hydrogen economy it is difficult to find specific reliability data. For the determination of reasonable safety distances (in standard development as well as in installation specific calculations) it is very important to continuously collect and file appropriate safety data and to make commonly agreed data available for the stakeholders.

One conclusion from this study and the comparison is that safety distance calculations specific to the solutions chosen for an installation is worth the effort as general recommendations can not reflect all possible variations in technical solutions. The EIGA method also has a potential for standardised recommendations for a specific station design: Comparing the “HyApproval station” to this station, the variation in safety distances is related to differences in pipe diameters, operational pressure and assumed safety equipment. It would however be recommendable to do a thorough review of the harm criteria and bring them more in line with recent research and accident experience.

**References**

[1] European Industrial Gases Association: Determination of Safety Distances. IGC Doc 75/07/E, 2007

[2] NFPA 55. Standard for the storage, use, and handling of compressed gases, and cryogenic fluids in portable and stationary containers, cylinders, and tanks. National Fire Protection Association, 2010

[3] 2003 International Fire Code. International Code Council

[4] ISO TS 20100, Gaseous hydrogen – Fuelling stations, 2008

[5] Christou&Porter, Guidance on land use planning as required by council directive 96/82/EC1999, Institute for systems informatics and safety 1999

[6] Tchouvelev et al, IEA HIA Task 19 Hydrogen Safety Effort In Developing Uniform Risk Acceptance Criteria For The Hydrogen Infrastructure, NHA 2008

[7] API Standard 521, Pressure-relieving and Depressuring Systems, 5$^{th}$ Ed., American Petroleum Institute, 2007

[8] PHAST 6.54, Material reference data: DIPPR 2000, © 1999-2007 Det Norske Veritas

[9] TNO Yellow book Methods for the Calculation of Physical Effects, Netherlands Committee for the Prevention of Disasters – CPR 14E, 3rd Ed 1997/online 2005

[10] HyApproval, AirLiquide, Handbook for Hydrogen Refuelling Station Approval Version: 2.1,June 4, 2008

[11] Lauridsen, Kozine, Markert, Amendola, Christou, Fiori; The ASSURANCE project, Final summary report, page 37 Risø-R-1344(EN), ISBN 87-550-3063-7

# Speaking of Safety: Learning from Safety Reviews

**Steven C. Weiner**, Pacific Northwest National Laboratory, USA
**Richard A. Kallman**, City of Santa Fe Springs, USA
**Edward G. Skolnik**, Energetics Incorporated

## 1 Introduction

Safety is an essential element for realizing expanded applications for hydrogen and hydrogen systems, including safe operation in all aspects – from production through storage, distribution and use; from research, development and demonstration to commercialization. The U.S. Department of Energy's Fuel Cell Technologies Program gives safety paramount importance through its goal to "develop and implement the practices and procedures that will ensure safety in the operation, handling, and use of hydrogen and hydrogen systems for all DOE-funded projects and utilize these practices and lessons learned to promote the safe use of hydrogen."[1] The Hydrogen Safety Panel (Table 1) formed in 2003 captures the relevant experience from the government, industrial and academic sectors to address this goal by helping DOE integrate effective safety planning into funded projects and by providing expertise and guidance to identify technical data gaps, best practices and lessons learned.

**Table 1: Hydrogen safety panel.**

| | |
|---|---|
| Richard A. Kallman, Chair | City of Santa Fe Springs, CA |
| Steven C. Weiner Program Manager | Pacific Northwest National Laboratory |
| Addison Bain | NASA (ret) |
| Harold Beeson | NASA White Sands Test Facility |
| David J. Farese | Air Products and Chemicals |
| William C. Fort | Shell Global Solutions (ret) |
| Don Frikken | Becht Engineering |
| Michael Pero | Hydrogen Safety, LLC |
| Glenn W. Scheffler | GWS Solutions of Tolland, LLC |
| Andrew J. Sherman | Powdermet Inc. |
| Ian Sutherland | General Motors |
| Robert G. Zalosh | Firexplo |
| Nick Barilo, Technical Support | Pacific Northwest National Laboratory |
| Edward G. Skolnik, Technical Support | Energetics Incorporated |

This paper describes the role and experiences of the Hydrogen Safety Panel in conducting and reporting on project safety reviews and what has been learned on post-review follow-ups with project teams. Work by the Hydrogen Safety Panel in reviewing project safety plans, conducting project safety reviews and supporting the development of safety knowledge tools has been previously reported.[2-4] For example, the work of the Panel helped in defining the construct and technical content for H2 Safety Best Practices (http://h2bestpractices.org). This website facilitates the availability of the wealth of knowledge and experience related to the safe use and handling of hydrogen that exists as a result of an extensive history in a wide variety of industrial and aerospace settings.

## 2 Safety Reviews Focus on Interaction and Knowledge Sharing

The project safety review provides one mechanism by which the Panel addresses the DOE program goal previously noted. Safety reviews are conducted as either a one-day site visit or telephone interview and focus interactions with project teams on learning, knowledge sharing and encouragement of thorough, continuous and priority attention to safety rather than as an audit or investigative exercise. For the more in-depth site visit safety reviews, the use of a protocol that is shared with the project team helps achieve the intended purpose.The telephone interview can serve to identify whether a site visit is warranted but it may also serve to focus on the discussion of a more specific topic, e.g. hydrogen storage and handling facilities. Since 2004, the Panel has conducted 36 safety reviews as either site visits or telephone interviews.

Projects for review are selected by a variety of means. For example, the Panel may recommend a site visit based on its review of the project safety plan or the need to discuss the safety aspects of the work because of a new phase/scale of work and/or its broader impact to other projects in the DOE portfolio. The Panel also seeks recommendations from DOE program staff who may request reviews for similar reasons. Safety reviews are conducted at a variety of organizations – government laboratories, large and small companies, and academic institutions. At the latter, students are encouraged to participate in the site visits which provide them an opportunity to learn from the safety related discussions.

Safety reviews are intended to raise safety consciousness directly at the project level by

- discussing various aspects of the project work
- enabling project staff to focus specifically on safety-related topics
- sharing and discussing new insights that bear on safety
- identifying project-specific findings that can have broader benefit

The safety review is meant to focus discussion on how the policies and procedures of the performing organization are applied toward the safe conduct of the project work.

The development of the safety review agenda and implementation of the reporting protocol is done interactively with the project team. This helps to ensure that safety issues and questions are discussed and lessons learned by project teams are captured. Unique to the final report are the project team’s responses to specific recommendations made by the review team. In this manner, DOE has a more comprehensive picture of the safety review, outcomes and perspectives of all of the participants when the final report is issued.

## 3 Measuring Outcomes from Safety Reviews

The final report that is issued to DOE contains a set of recommendations. The authority to require action by the project team on any recommendations resides solely with the responsible DOE contracting officer. Experience suggests that in some cases, recommendations are voluntarily completed by the project team even before the final report is issued. Nonetheless, the consensus of the Panel suggested a need to establish a follow-up protocol with project teams in order to identify actions, conclusions and findings as one means for measuring the value of this work. Action on report recommendations represents a rich source of safety knowledge that can have broader benefits to others. Weiner reported in May 2009 that 85 recommendations were provided in eight site visit safety review reports issued to DOE in the past two years. [5]

For the first set of follow-up interviews, five projects were selected for which safety review site visits were conducted in 2007 and 51 recommendations were contained in the five final reports. The projects represented both university-based laboratory-scale work as well as hydrogen fueling infrastructure projects. Each interview focused the discussion as follows:

- How were recommendations acted upon?
- What changes were imparted by action on the recommendations?
- Were there other changes made that affect safety aspects?
- Are there any additional lessons learned to share?

Table 2 summarizes the set of recommendations discussed in the five follow-up interviews and characterizes the specific topics of discussion.

**Table 2: Categorizing recommendations and actions taken.**

| Category | Recommedations Implemented | Partial or In Progress | No Action or Rejected | Total Recommendations |
|---|---|---|---|---|
| Safety Vulnerability/ Mitigation Analysis | 9 | 2 | 4 | 15 |
| System/Facility Design Modifications | 3 | 2 | 1 | 6 |
| Equipment/Hardware Installation and O&M | 5 | 3 | 0 | 8 |
| Safety Documentation | 4 | 4 | 0 | 8 |
| Housekeeping | 3 | 2 | 0 | 5 |
| Emergency Response | 5 | 2 | 2 | 9 |
| Total | 29 | 15 | 7 | 51 |

Any specific recommendation may actually overlap more than one category. Approximately 30% of the recommendations – 15 in number – focused on some type of safety-related analysis. The identification of safety vulnerabilities (ISV) and subsequent analysis is a significant topic in the safety planning discussion at such safety reviews. Whereas the policies, procedures and methodologies for such work are usually well established at private sector organizations involved in demonstration projects, such is often not the case at universities conducting experimental work. Specific references including the DOE safety guidance document are often provided at these safety reviews to help with such analyses.[6] The first set of follow-up interviews was conducted approximately two years after the initial safety reviews. In one such interview, it was clear to the Panel that the interview process itself served as a catalyst for the project team to initiate, continue or restart action on the Panel's recommendations. More timely scheduling of future follow-up interviews should help with our objective of achieving priority attention to safety at the project level.

The follow-up interview provides an opportunity for project teams to share and discuss additional safety lessons learned. During the course of two follow-up interviews, the Panel became aware of two safety events involving dispensing/breakaway hose systems. These safety events were discussed at a Panel meeting and each contractor consented to submit and post a safety event record to the publicly available Hydrogen Incident Reporting and Lessons Learned Database (http://h2incidents.org).

The Panel concluded that all interviewees have improved the safety aspects of the work they are conducting. Overall, 86% of the recommendations – 44 in number – have been implemented in some manner or are in progress for the set of five projects which were interviewed.

Follow-up with project teams will now become an integral part of the safety review protocol. It is expected that such follow-up will be conducted within 6-9 months after the final report is issued, specifically determined on a project-by-project basis. Factors to be considered include the nature and number of recommendations as well as how safety insights gained might have broader value to the Hydrogen Safety Panel and the DOE program. The Hydrogen Safety Panel has recently taken an action to ask its safety review teams to qualitatively prioritize the set of recommendations for any given report. This prioritization will be helpful to DOE for actions it wishes to take regarding project safety and will also help focus the discussion during future project follow-up interviews.

## 4 Concluding Thoughts

Project safety reviews have proven to be an effective means for the Hydrogen Safety Panel to support the goals and objectives of the DOE Fuel Cell Technologies Program. Additionally, safety review follow-up interviews have provided an impetus for projects to refocus on safety. We have noted how safety at the project level is best served. The mechanism used by the Panel for seamless discussion and knowledge sharing at the project level augments the prime responsibility of any organization to ensure the safe conduct of work. One project manager noted "not only did it reinforce the importance of safety, we benefited from having experts available for discussions."[7] The Hydrogen Safety Panel seeks to replicate that approach and sentiment many times over.

## Acknowledgments

The authors wish to thank the DOE's Fuel Cell Technologies Program (Richard W. Farmer, Acting Program Manager; Antonio Ruiz, Safety, Codes and Standards Team Leader) for their support of this work.

## References

[1] "Hydrogen, Fuel Cells and Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015," Page 3.8.1. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

[2] Weiner, S.C., Kinzey, B. and Skolnik, E.G., "Hydrogen Safety Review Panel: Shaping Safety Awareness," 20th Center for Chemical Process Safety International Conference," Atlanta, GA, April 12, 2005.

[3] Weiner, S.C., Kallman, R.A., Ruiz, A. and Schneider, J.M., "Hydrogen Safety: From Policies to Plans to Practices," Paper 100068, International Conference on Hydrogen Safety, Pisa, Italy, September 8-10, 2005.

[4] Weiner, S.C. and Barilo, N.F., "Hydrogen Safety Panel: Shaping Safety Awareness and Practice," 2008 Mary Kay O'Connor Process Safety Center International Symposium, College Station, TX, October 28-29, 2008.

[5] Weiner, S.C., "Hydrogen Safety Panel," Presentation SCS07, 2009 DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, May 22, 2009.

[6] "Safety Planning Guidance for Hydrogen Projects, November 2007," U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Program. (http://www1.eere.energy.gov/hydrogenandfuelcells/codes/oversight.html)

[7] Slattery, D., personal communication, University of Central Florida, 2009.

# Safety Aspects of Hydrogen Fuel Cell Vehicles

**Christian Sachs**, **André Mack-Gardner**, Adam Opel GmbH, Germany

Hydrogen fuel cell vehicle safety generally focuses on three areas of vehicle safety: The fuel, the storage system, and the vehicle itself. This presentation will give an overview using the Opel HydroGen4, equipped with a 70 MPa compressed hydrogen storage system, as an example [1].

Like any fuel, hydrogen has a significant amount of chemical energy which will be released upon ignition if an oxidizer such as oxygen is available. In air, mixtures between 4 vol% H2 (lower flammability limit, LFL) and 74 vol% H2 (upper flammability limit, UFL) are ignitable [2]. An unintended release of hydrogen itself is not a threat as hydrogen is not toxic, but the possible risk of ignition needs to be considered in the safety assessment.

For gasoline-driven vehicles, gasoline fuel leaks can be detected in two ways. First, it is a fluid and leakages are directly visible. Second, gasoline has a characteristic smell so that some discharges may also be detected directly. In contrast, hydrogen gas is invisible and odorless. However, depending on the storage technology, additional signs of leakage may be noticeable [3]. For example, for high-pressure storage systems a leak in the high-pressure section is audible, and for liquid hydrogen systems, leakages could be visible. In any event, hydrogen sensors are used to detect hydrogen at concentration levels higher than the specific target values. In the future, by odorizing the hydrogen fuel or advanced process monitoring methods, it may be possible that hydrogen sensors will no longer be necessary.

The severity of a possible ignition is predominantly proportional to the total mass of released hydrogen. However, the released mass cannot be determined easily as a hydrogen sensor detects the concentration of hydrogen only. Therefore, it is possible that a very small mass of hydrogen released causes a concentration detected above the ignition threshold, even though the actual average concentration is lower than the ignition threshold. Due to its buoyancy and diffusivity, the released hydrogen could spread in a way that only a very small area exceeds LFL. Moreover, the LFL limit is applicable to laboratory conditions and marks the transition from the region where no ignition is possible to the region where ignition is barely possible under some conditions. Thus, for a detailed study, in particular the flame propagation needs to be taken into account [4]. Considering dynamic and usual automotive environmental conditions, the actual sustainable ignition threshold is significantly above LFL [5,6].

On board the HydroGen4 fuel cell vehicle, there are seven hydrogen sensors for hydrogen leakage supervision. If the onboard supervision system detects hydrogen concentrations exceeding the threshold values, a hydrogen warning mode is enabled. The vehicle driver is notified by visible and audible signals, and fuel supply from the hydrogen storage system is shut down by closing shutoff valves. However, the driver needs to safely park the vehicle and therefore, propulsion needs to be available. Hence, propulsion in the hydrogen warning mode is provided by using the vehicle’s high-voltage traction battery.

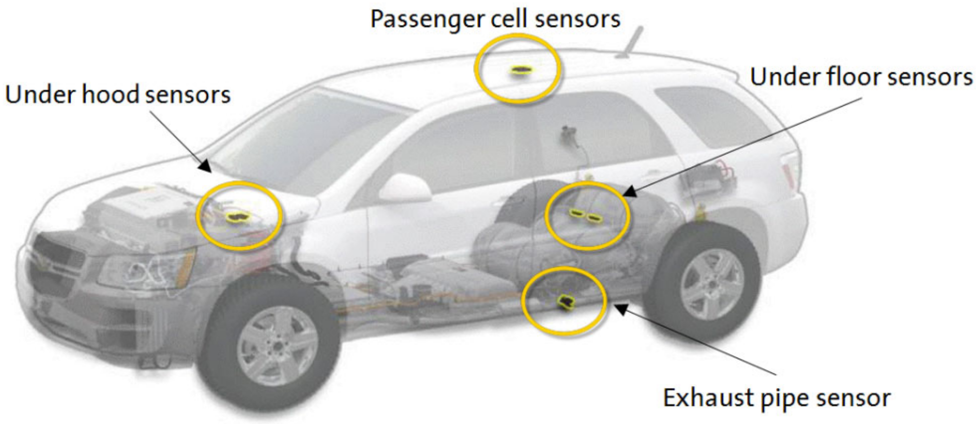



**Figure 1: Location of hydrogen sensors onboard the HydroGen4.**

There are two challenges for the onboard supervision system: First, leakages must be detected in a timely manner. Therefore, the sensors need to be placed at selected locations. For the HydroGen4, great care has been spent in validation testing and concentration threshold assessment to define those locations. For example, the Background Oriented Schlieren Method has been refined and applied to study vehicle-level hydrogen dispersion in great detail (Figure 2) [7]. As a result, hydrogen sensors have been placed at the four locations shown in Figure 1. Second, the sensor functionality needs to be verified anytime. As under normal operating conditions no hydrogen concentration is detected, it is impossible to perform a sensor check without additional measures like e.g. hydrogen test gas which could be applied in regular vehicle service checks. Therefore, hydrogen sensors with very high reliability must be used and critical locations are currently supervised with redundant sensors.

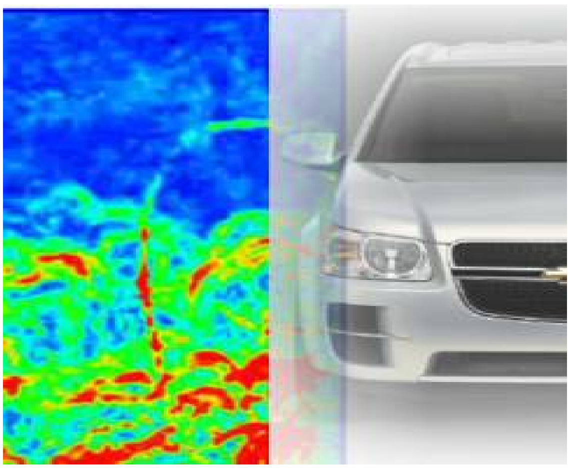


**Figure 2: Background Oriented Schlieren (BOS) technique to assess hydrogen dispersion.**

In terms of safety, the main task of any hydrogen storage system is to contain and seal the hydrogen. The shutoff approach applies to failure detection in normal operating condition and to vehicle crash situations. To provide the vessel integrity under very harsh conditions, there are several tests required by applicable safety codes including permeation testing, drop testing (Figure 3), vibration testing, extreme temperature testing, bonfire and gunfire testing. Most of the tests are to validate vessel performance under usual operating conditions over the vehicle's life, i.e. testing under very harsh conditions and validating the system's performance under these conditions. However, the bonfire test and the gunfire test are of destructive nature and assess functionality under worst case assumptions. The bonfire test is designed to verify that during vehicle fires affecting the vessel's integrity, the vessels are depressurized by an intended hydrogen release. In the gunfire test, the vessel is penetrated by a bullet. It is a test to verify that after vessel penetration, there is just a discharge of hydrogen rather than a vessel rupture. However, integrated in a vehicle, vessel penetration of the storage system is very unlikely even during extreme vehicle accidents. Even though the HydroGen4 withstands severe impact conditions, an additional internal test program for the storage vessels has been initiated. Several vessels have been tested against extreme impact conditions at various hydrogen pressures up to 70 MPa. In this test program, all vessels remained leak-tight and no pressure drop was observed.

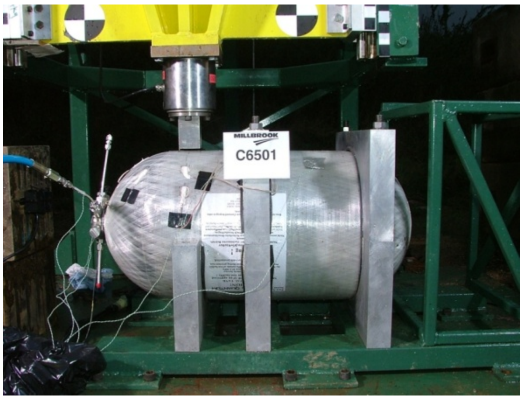



**Figure 3: Drop test of HydroGen4 storage vessel.**

Concerning Hydrogen Safety, Fuel cell vehicles need to meet the applicable regulations, in particular the Federal Motor Vehicle Safety Standards FMVSS 208 and FMVSS 301 for the U.S. The HydroGen4 was designed from the beginning to meet these and other requirements. Extensive computer modeling and simulation has been performed together with accompanying component and subsystem tests. A final test according to FMVSS 208 was run on full vehicle level with an operating fuel cell and hydrogen on board. Of particular interest from a hydrogen safety perspective is the rear crash as in this test, the storage system is exposed to external loads. In the rear crash according to FMVSS 301 (Figure 4), a barrier with a mass of 1368 kg hits the standing vehicle from the rear with 70% offset at a speed of 80.5 km/h. Also this test was performed with the HydroGen4 and the vehicle sensing system worked successfully as expected. The main shutoff valves closed automatically thereby inhibiting any further external leakage.

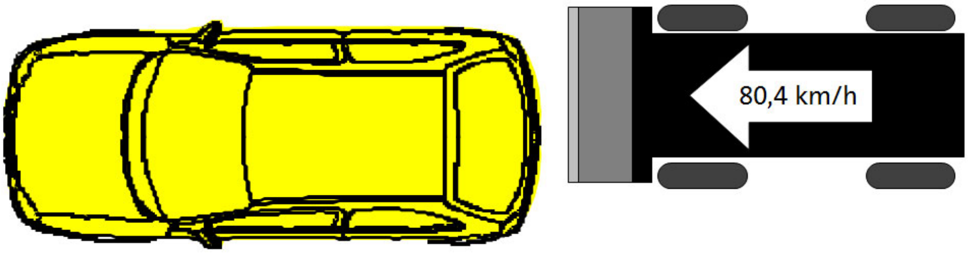



**Figure 4: Schematic of barrier test according to FMVSS 301.**

In summary, safe onboard handling and storage of hydrogen is verified for fuel cell vehicles. Hydrogen leakages are detected by hydrogen sensors and tank system shutoff valves are closed automatically. Concerning Hydrogen Safety, the HydroGen4 meets all applicable regulations, in particular FMVSS 208 and FMVSS 301. In addition, the storage vessels have been tested for extreme impact conditions at various hydrogen pressures up to 70 MPa.

## References


[1] Bork, M., “Electric propulsion, hydrogen, and fuel cell technology – an integrated approach“, fcell 2008, Stuttgart, Germany.

[2] Chemical Properties Handbook, edited by Yaws, C.L., 1999, McGraw-Hill.

[3] Simon, J.M., et al., “Guidelines for Use of Hydrogen Fuel in Commercial Vehicles”, DOT Report No. FMCSA-RRT-07-020, 2007.

[4] Swain, M.N., et al., “Gaseous fuel transport line leakage - natural gas compared to hydrogen”, pp 161-170 in Alternative Fuels: Alcohols, hydrogen, natural gas and propane (SP-982), Proceedings of 1993 Society of Automotive Engineers’ Future transportation technology conference, San Antonio, TX, Aug 9-12, 1993.

[5] Keller, J., Bénard, P., “Hydrogen Behavior – Myth Busting“, The International Conference on Hydrogen Safety, San Sébastian, Spain, 2007.

[6] Corfu, R., DeVaal, J., Scheffler, G.,“Development of Safety Criteria for Potentially Flammable Discharges from Hydrogen Fuel Cell Vehicles“, SAE World Congress, 2007, Detroit, MI.

[7] Mack-Gardner, A., Kessler, A., Ehrhardt, W., “Validation of Hydrogen Safety relevant CFD Simulations with a Background Oriented Schlieren Method”, submitted to SAE World Congress, 2011, Detroit, MI.

# Study on the Fire Response of Vehicles with Compressed Hydrogen Cylinders

**Yohsuke Tamura**, **Junichi Tomioka**, **Jinji Suzuki**, Japan Automobile Research Institute, Japan

**Abstract**

To investigate the events that could arise when fighting fires in vehicles with compressed hydrogen CFRP (carbon fiber reinforced plastic) composite cylinders, we conducted experiments to examine whether a hydrogen jet flame caused by the activation of the pressure relief device (PRD) can extinguished and how spraying water influences the cylinder and PRD. The experiments clarified that the hydrogen jet flame cannot be extinguished easily with water or dry powder extinguishers and that spraying water during activation of the PRD may result in closure of the PRD, but is useful for maintaining the strength of CFRP composite cylinders for vehicles.

## 1 Introduction

For gas fires in common buildings, the compressed industrial cylinders are cooled by spraying water to prevent rupture of the vessel due to the heat of fire [1]. However, the vessels used in facilities are made of steel, and there have been no reports on whether the measures used for steel cylinders can also be applied to CFRP storage cylinders that are now being used on vehicles.

On the other hand, according to the emergency response guide of the compressed hydrogen fuelled vehicle [2], water should not be sprayed on the vent section of the jet flame because of the risk of explosion when the hydrogen jet diffusion flame is extinguished.

This paper reports experiments that evaluate what risks may be present if firefighters spray water on burning composite cylinders and extinguish the jet flame. This information can be used to re-evaluate common guidance that firefighters do not extinguish fire involving onboard gaseous storage.

## 2 Extinguishment Test of Hydrogen Jet Flame

We investigated whether the hydrogen jet flame can be extinguished with water spray or powder quenching.

### 2.1 Test method

Figure 1 schematically depicts the test apparatus.

Hydrogen gas supplied from the vessel (15 MPa, 47 Liters) blows out into the atmosphere through the vent port (blowout aperture: 4.2 mm), simulating a gas emission hole in the event of PRD activation, and is ignited by an electric spark. The spraying water or a dry powder extinguishing agent (ABC fire extinguishing agent for automobiles) was aimed directly at the vent port. A water-spray nozzle with a maximum water discharge volume of 500 L/min$\cdot$m$^2$

and a 2 inch nominal diameter was used for extinction with water spray. A vehicle fire simulator was tested on asphalt pavement by connecting vent tubes to it.

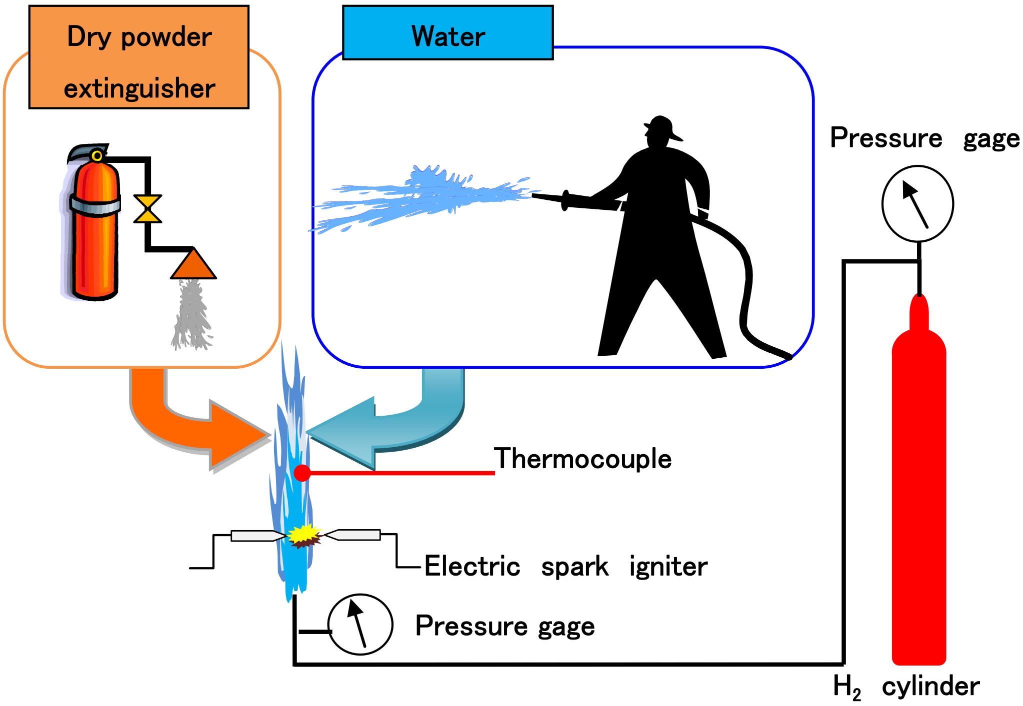



**Figure 1: Schematic of test system.**

Two directions of vent port were used: upward and inclined downward by 45°. The vent port directed upward was installed at the centre of the rear portion of the roof of the vehicle simulator, and that inclined downward was installed under the floor near the rear-wheel shaft of the vehicle.

The fire fighting was executed from forward or the rear side of the vehicle within the range from 1 to 5 meters.

Whether the flame was extinguished or not was determined by a thermocouple and infrared thermography.

## 2.2 Results

Figure 2 depicts an example of testing, and Table 1 presents the test results.

In the case of upward hydrogen discharge under the conditions shown in Table 1, it was not possible to extinguish the hydrogen jet flame by water spray or powder quenching at the vent port. Similarly the hydrogen jet flame was not easily extinguished in the case of 45° downward hydrogen discharge; however, extinction was observed in Test #4 when the blowout pressure from the vent port declined to 0.9 MPa. At a blowout pressure level of 0.9 MPa, the flame length was less than 50 cm while for a hydrogen storage cylinder of up to 50 litres capacity the blowout pressure would further drop to zero within a minute. In Tests #7 and #8, the hydrogen jet flame was extinguished at a blowout pressure of 0.3 and 0.2 MPa respectively; then, reignition occurred seconds after extinction due to the heated asphalt. In the vehicle fire simulator experiment, however, reignition even when it occurred did not cause any harmful events such as an explosion because the experiment was conducted on an open-air site with no enclosed spaces for hydrogen to gather.

These results suggest that the hydrogen jet flame generated by activation of the PRD of an actual vehicle cannot be easily extinguished by water spray or powder quenching; however, after once being extinguished, reignition at a low exhaust pressure is not harmful.

(a) Test 1, Upward vent, Water

(b) Test 7, 45 deg. diagonal backward vent, dry powder extinguisher

**Figure 2: Bonfire test scene.**

**Table 1: Results of hydrogen jet flame extinguishing test.**

| # | Venting direction | Extingusher (Orientation) | Results |
|---|---|---|---|
| #1 | Upward | Water (Forward side of the vehicle) | Non-extinguished |
| #2 | | | |
| #3 | | Dry powder extinguisher (Rear side of the vehicle) | |
| #4 | 45 degree diagonal backward | Water (Forward side of the vehicle) | Extinguished at the vent pressure 0.9MPa. |
| #5 | | | Non-extinguished |
| #6 | | Water (Rear side of the vehicle) | |
| #7 | | Dry powder extinguisher (Rear side of the vehicle) | Extinguished at vent pressure 0.3MPa. Reignition by the hot asphalt. No-explosion. |
| #8 | | | Extinguished at vent pressure 0.2MPa. Reignition by the hot asphalt. No-explosion. |

## 3 Influences of Water Spray in Fighting Fire around the Cylinder and PRD

We investigated the events that occur in the cylinder and PRD when they are heated by fire and then cooled by water spray, as well as the influences of water spray on the strength of the cylinder.

### 3.1 Test method

Figure 3 schematically depicts the test process for observing the cylinders and PRD after being heated by fire and then sprayed with water and evaluation of the influences on the strength of cylinders.

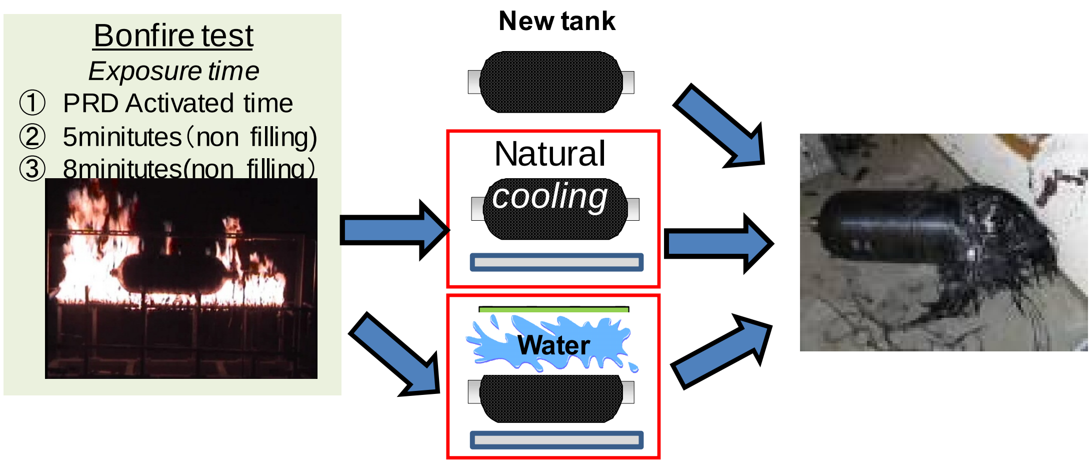



**Figure 3: Test process for evaluation on the strength of cylinders.**

An aluminum lined carbon fiber wrapped cylinder (Type 3; maximum filling pressure 35 MPa; capacity 39 Litters) was used for the sample cylinder, and tests (sample preparation) were conducted under the following six conditions.

**Sample 1**

The test cylinder equipped with in-tank solenoid valve was filled with hydrogen gas at 35 MPa. A PRD (activated temperature 105±5ºC) was mounted directly on In-tank valve. The bottom of the cylinder placed on its side was exposed to the flame from a propane burner. The burner was turned off as soon as the PRD operated. Water was then sprayed over the whole cylinder.

**Sample 2**

A test cylinder without hydrogen was exposed to the flame during the same period as for Sample 1, and then left alone after the burner was turned off.

**Samples 3 and 4**

The test cylinder without hydrogen was exposed to the flame for 5 min. Sample 3 was cooled by water spray, and Sample 4 was left alone.

**Samples 5 and 6**

The test cylinder without hydrogen was exposed to the flame for 8 min. Sample 5 was cooled by water spray, and Sample 6 was left alone (natural cooling). It should be noted that when this cylinder was filled with hydrogen at 35 MPa and exposed to the flame with no PRD installed, it ruptured in 416 sec (about 7 min) [3]. Therefore, the strength of the cylinder definitely deteriorates when the cylinder is exposed to the flame for 8 min.

In addition to the above cylinder Samples 1 through 6, cylinders with a history of non-exposure to flame were also tested to measure their withstanding pressures as an indicator of the deterioration of cylinder strength.

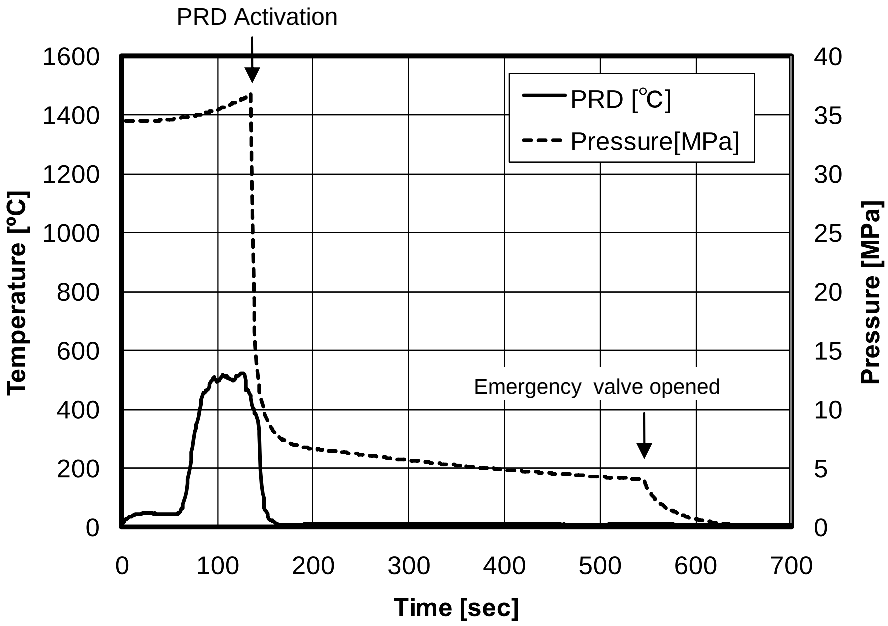
The cylinder prepared under each of these conditions was subjected to the burst tests specified in Japanese Hydrogen Storage Regulations (JARI S-001) [4] to check its burst pressure.

### 3.2 Test results

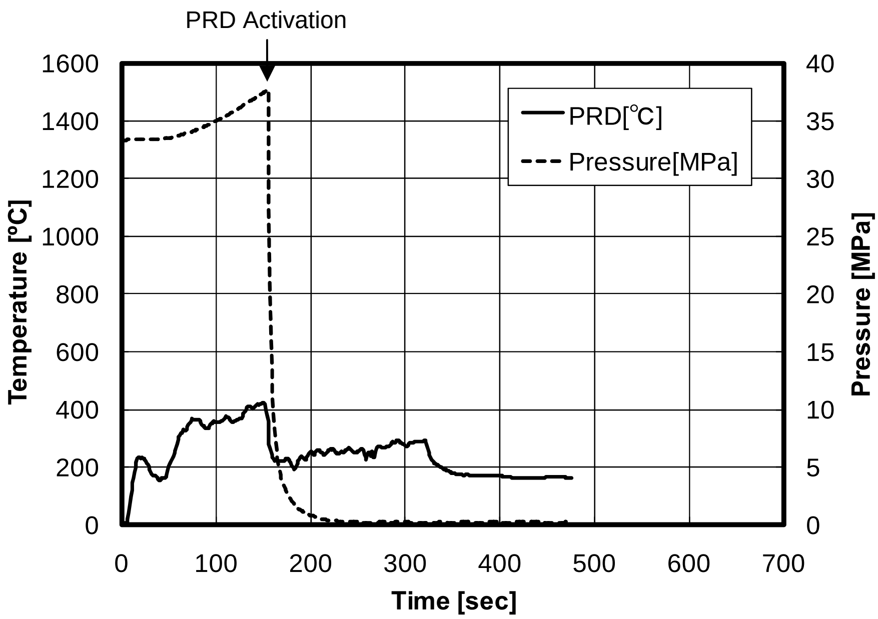
Figure 4(a) depicts the testing situation on Sample 1 when the PRD was activated, and Figure 4 plots the internal pressure of the cylinder and the ambient temperature of the PRD. When the whole cylinder was cooled with water while the PRD was activated, hydrogen was vented for 4 minutes or more. Therefore, to conduct the test safely, the gas in the cylinder was forcibly exhausted by installing a separate emergency vent valve.

Figure 4(b) indicates the internal pressure of the cylinder and the ambient temperature of the PRD of the same cylinder when it was not cooled with water, as had been done previously, for comparison.

Usually, the vent of hydrogen gas ends 1 minute after the PRD is activated. The fusible plug of the PRD, which is composed of a metal with a low melting point, could have resolidified by cooling, resulting in partial closure of the channel for exhausting hydrogen and extending the time for the hydrogen to exhaust. Incidentally, although the current rules do not include any regulation on reclosure of PRDs, PRDs constructed to avoid reclosure have already been developed and put into practical use.




(a) Cooled by water spray after activation of PRD




(b) Natural cooling

**Figure 4: Internal pressure and PRD temperature.**

Figure 5 depicts the relationship between the duration of flame exposure and the burst pressure in the burst test.

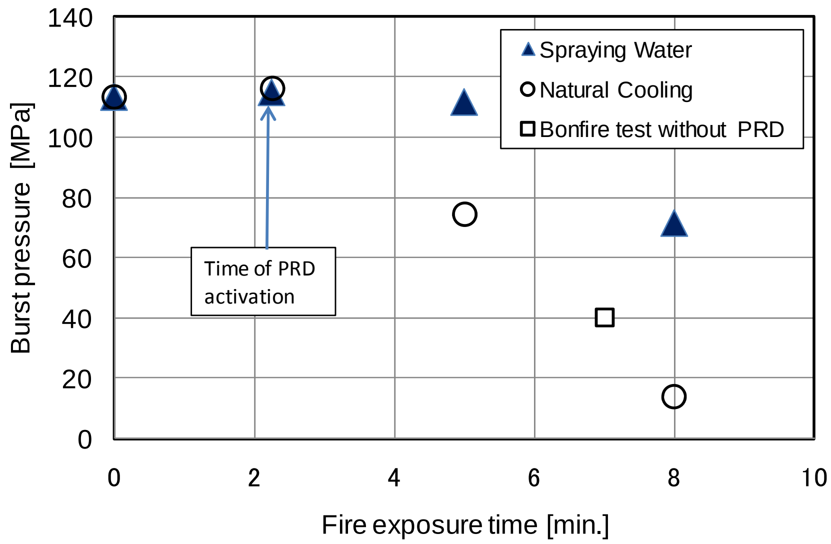



**Figure 5: Influence of increase in flame exposure time on burst pressure of cylinders after bonfire tests.**

Here, the burst pressure indicated at a flame exposure of 0 min is the withstanding pressure of the test cylinder itself (110.3 to 116.2 MPa). The □ mark shows the burst pressures and burst time of cylinders having no PRD and filled with hydrogen to a 35 MPa internal pressure in bonfire tests [3].

Regardless of whether the cylinder was cooled with water or left alone immediately after flame exposure to flame was stopped till the activation of the PRD (in 2 minutes and 15 seconds), the withstanding pressure of the cylinder was the same as that of the test cylinder itself; therefore, no deterioration in burst resistance strength was observed.

After 5 minutes of exposure to the flame, the burst pressure decreased only when the cylinder was left alone. Furthermore, after 8 minutes exposure to the flame, the burst pressure decreased for both cooling with water and leaving alone; however, the strength of the cylinder was still higher when the fire was extinguished with water spray.

The reason for the difference in cylinder strength between cooling with water and leaving alone when the cylinder was exposed to the flame for 5 minutes or more is considered to be as follows. When this cylinder is exposed to the flame for 5 minutes or more, the cylinder itself burns; thus, combustion continues after the fire source is removed when the cylinder is left alone, and the cylinder remains at a high temperature for a longer time. Combustion of the CFRP compound cylinder itself is caused by heat decomposition of the resin used to bundle carbon fibers. More resin comes off as combustion continues[5], resulting in deterioration of the cylinder; therefore, it can be assumed that the withstanding pressure differed between cooling with water and leaving alone when the cylinder was exposed to the flame for 5 minutes or more. From these results, it was determined that the CFRP compound cylinder is advantageous in terms of strength when self-combustion is prevented by cooling with water rather than letting it cool slowly by leaving it alone.

In addition, the present study indicated that it is also possible to evaluate deterioration of the strength of cylinders by conducting burst tests.

## 4 Conclusions

To identify problems and to examine and prepare countermeasures for firefighting and rescue activities for fires of vehicles with compressed-hydrogen cylinders, we investigated (1) the possibility of extinguishing the hydrogen jet flame that forms when the PRD activates and (2) the influences of water spray on the cylinder and the PRD for firefighting. We clarified the following:

1. The hydrogen jet flame that is formed when the PRD operates cannot be extinguished easily with water spray or powder quenching.
2. If water spray for firefighting is applied directly on the cylinder or PRD while the PRD is operating, the type of PRD used in this study could reclose.
3. The strength of the CFRP compound cylinder is better maintained when water spray is used for firefighting. These results suggest that neither a large explosion nor deterioration of the strength of the cylinder is caused by extinction of the jet flame in an open space if the vehicle is equipped with a PRD that does not reclose upon fire extinction with water spray.

Many issues remain unexplored. It has not been determined whether the cylinder remains filled with hydrogen gas after the fire has been extinguished; if it does, it is not known how to dispose safely of such a cylinder. Therefore, it is necessary to examine and develop measures for such cases.

**Acknowledgements**

This study is a summary of part of the results of the "Establishment of Codes & Standards for Hydrogen Economy Society" which was implemented as a study consigned by the New Energy and Industrial Technology Development Organization (NEDO).

**References**

[1] Guidelines for Gas Cylinder Safety, BOC Limited(2008) http://safety.chemistry.unimelb.edu.au/pdf/BOC_Guidelines_for_Gas_Cylinder_Safety.pdf

[2] International Chemical Substance Safety Card, California Fuel Cell Partnership, Emergency Response Guide, Version 2, 2004

[3] Yohsuke Tamura, Masashi Takahashi, Yasumasa Maeda, Hiroyuki Mitsuishi, Jinji Suzuki, Shogo Watanabe, Fire Exposure Burst Test of 70 MPa Automobile High-Pressure Hydrogen Cylinder, JSAE Technical Paper No. 20065622, Society of Automotive Engineers of Japan(2006)(Japanese)

[4] JARI-S001, Japan technical standards for containers for compressed-hydrogen vehicle fuel device (2004)(Japanese)

[5] Nakanishi Yoichiro, KimoteMasaki, Awaji Toshio, Influence of Fiber, Matrix Resin and Additive on the Pyrolysis and Combustion Processes of FRP in Air, Journal of the Society of Materials Science, Japan, Vol. 45, No.10(1996) (Japanese)

# Damage Detection in High-Pressure Storage Cylinders

**Michael Sulatisky**, Dan Mourre, SRC, Saskatoon, Canada
**D. Robert Hay**, TISEC Inc., Montreal, Canada

## 1 Introduction

Gaseous fuels stored at pressures up to 700 bar (10,000 psig) have created a need for an on-line damage detection system similar to the on-board diagnostic system for detecting faults in automotive components [1, 2, 3, 4]. The goal was to develop a low-cost system for detecting cuts, holes, and delamination in tanks as shown in Figure 1.

**Figure 1: Dual-fuel hydrogen-gasoline truck and storage tank installation.**

Electromagmetic, resistive, and ultrasonic methods were investigated. Funding and technical support were provided by Natural Resources Canada, Precarn Inc., Dynetek Industries, the University of Saskatchewan, and General Motors of Canada.

## 2 Electromagnetic Method

When an electromagnetic wave passes through a carbon fiber/epoxy composite, the incident magnetic field attenuates based on the frequency, conductivity, magnetic permeability, and the thickness of the material [5, 6, 7, 8]. If the composite material is damaged via fiber breakage, or delamination, the local conductivity will change and the amplitude of the magnetic field passing through the material will also change [9, 10]. Monitoring the amplitude of the wave residual passing through the composite can be utilized as a damage indicator.

Piezoelectric sensors made of polyvinylidene difluoride (pvdf) were imbedded into the carbon fiber matrix of storage tanks, as shown in Figure 2. The electromagnetic technique indicated the system was capable of detecting cuts, gouges, delamination, fatigue, heat, and stress rupture well before a leak was initiated. The tests were conducted on forty 33-L, 200-bar (3000-psi) tanks supplied by Dynetek Industries. However, although damage was detected, the receiving signals from the sensors did not show a robust, reliable response to damage.

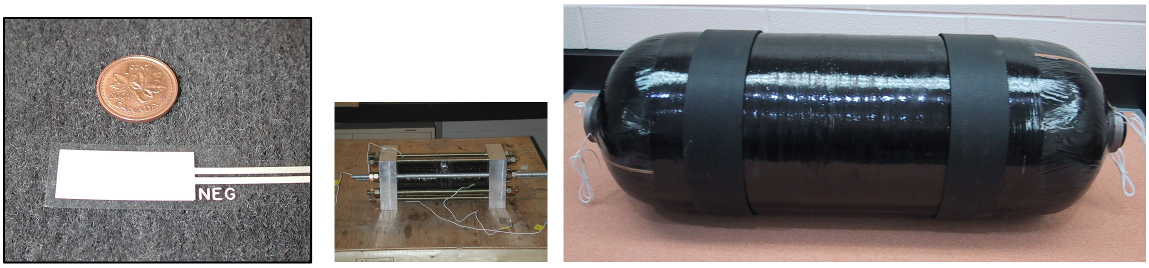



**Figure 2: PVDF sensor, tank modules, and 33-L Dynetek storage tank.**

## 3 Resistive Measurement

An alternative to the electromagnetic method is to directly measure the resistance of the carbon fiber as a function of resistivity, length, and cross-sectional area of fiber. If a carbon fiber is broken, the resistance of that fiber will become infinite [11, 12, 13]. If it is damaged, the resistance will increase by a finite amount.

The relationship between resistance and damage was first investigated in tank modules wound with carbon fiber, as shown in Figure 2. The results indicated that circumferential measurements were highly sensitive to impact and cut damage. Axial measurements were found to be less sensitive, but more repeatable. When the research was extended to pressurized cylinders, results obtained were similar to un-pressurized results in the axial case, but poor in the circumferential scenario. It was found that the carbon-fiber wrap must be electrically isolated from the aluminum liner, which was difficult to achieve as the tank expanded and contracted due to pressure changes.

## 4 Ultrasonic Method

Long-range ultrasonic testing is based on the reflection of ultrasound from an area where the sound wave meets a change in wall thickness caused by a flaw, or on the attenuation of the ultrasonic as it is transmitted past such an area, as shown in Figure 3 [9, 10]. In thin shells the ultrasonic wave is guided by the wall surfaces as plate or Lamb waves that penetrate the complete wall thickness.

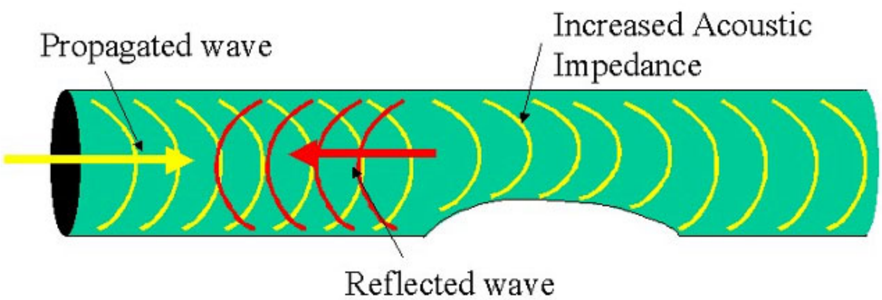



**Figure 3: Ultrasonic wave moving through a tank wall.**

Three types of ultrasonic transducers were evaluated, as shown in Table 1.

**Table 1: Comparison of the transducers evaluated for cylinder inspection.**

| Transducer | Technical Description | Advantages/Disadvantages |
|---|---|---|
| Broadband piezoceramic  | 0.5-MHz center frequency<br>0.1 to 1-MHz range<br>25-mm diameter element<br>25 x 37.5-mm footprint | Robust<br>Expensive ~ $350/transducer<br>Large footprint – 1.5 x 1”<br>Rigid – requires machining to conform surface<br>Piezoceramic may be damaged by impact |
| Piezoceramic Disk  | 375-kHz radial center frequency<br>5-MHz thickness center frequency<br>6-mm diameter | Simple disk embedded on cylinder surface.<br>Relatively inexpensive ~ $10/disk in moderate volumes<br>Straight forward installation procedure<br>Adequate signal-to-noise ratio at low to moderate excitation voltages<br>Rigid – requires machining to conform to surface<br>Piezoceramic may be damaged by impact |
| Piezoploymer Film  | 10-MHz center frequency<br>110-µm thick<br>13 mm x 13 mm footprint<br>Copper tape electrodes<br>Wide frequency range | Supplied in large flexible sheets<br>Tough material can survive impact damage<br>Flexible material conforms to surface<br>Relatively inexpensive ~ $400/18”x24” sheet.<br>No adhesive or gel coupling is required<br>Comparably weak transmitter/receiver at the cylinder testing frequencies since 110-µm material has 10-MHz resonance. |

A piezoceramic disk sensor installation is shown in Figure 4, along with a sample waveform demonstrating an excellent signal-to-noise (SNR) ratio.

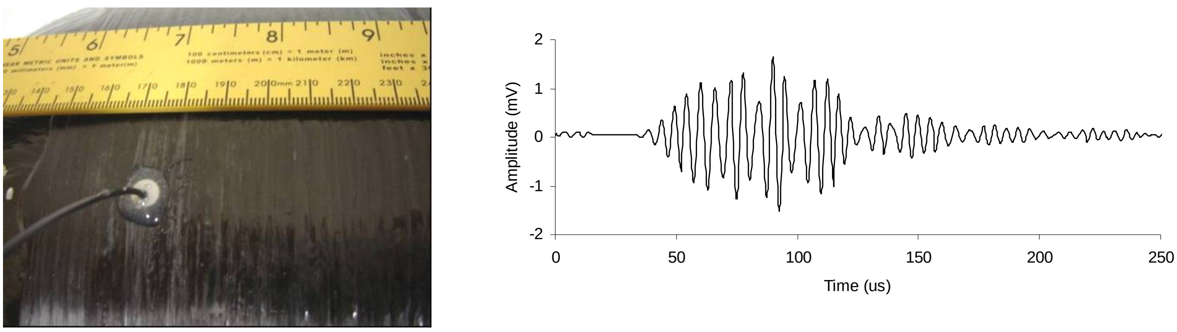



**Figure 4: Piezoceramic disk mounted on cylinder and signal-to-noise ratio.**

Wave-speed and attenuation characteristics were determined to identify a suitable sensor to generate and receive ultrasound efficiently while mounted on the surface of the tank. It was found that the optimum long-range ultrasound frequency modes were 190 kHz and 322 kHz for axial and circumferencial inspection, repectively. Damage detection tests evaluated the sensitivity of these frequency modes to parallel cuts, perpendicular cuts, small diameter holes, and mechanical impact damage. None of the damage introduced resulted in leakage from the tank.

## 5 Damage Detection Procedure

While time-of-flight and amplitude are commonly used ultrasonic signal features for defect detection, this work used the cross-correlation coefficient to generate a "signature" or reference waveform immediately after the installation of the sensors. This approach accommodates any changes in the acoustic response of the tank due to manufacturing and installation differences. It is a statistical comparison between the signal in the present state and the signal in the reference state, which is an indication of the damage inflicted on the tank. The reference data set ($s_j$) is acquired immediately after initial installation of the sensors. All future data ($s_k$) are compared to the initial data set for damage calculation.

## 6 Damage Detection Results using Ultrasonics

Transverse cuts and axial notches, 3-mm diameter drilled holes, and impact damage via steel mallet were introduced into a cylinder at various locations. A 1.5-mm thick grinding wheel was used to cut the notches, and a 3-mm diameter drill bit was used to cut a hole 5-mm deep into the carbon-fiber composite material without cutting through.

The damage detection result for impact using a hammer is shown in Figures 5. In this figure the reference waveform acquired before impact is shown as a blue dashed line, and the data acquired after damage is shown as a solid black line which is greatly attenuated. The test setup demonstrates that it is possible to detect damage located midway in the cylinder using sensors on opposite ends of the cylinder.

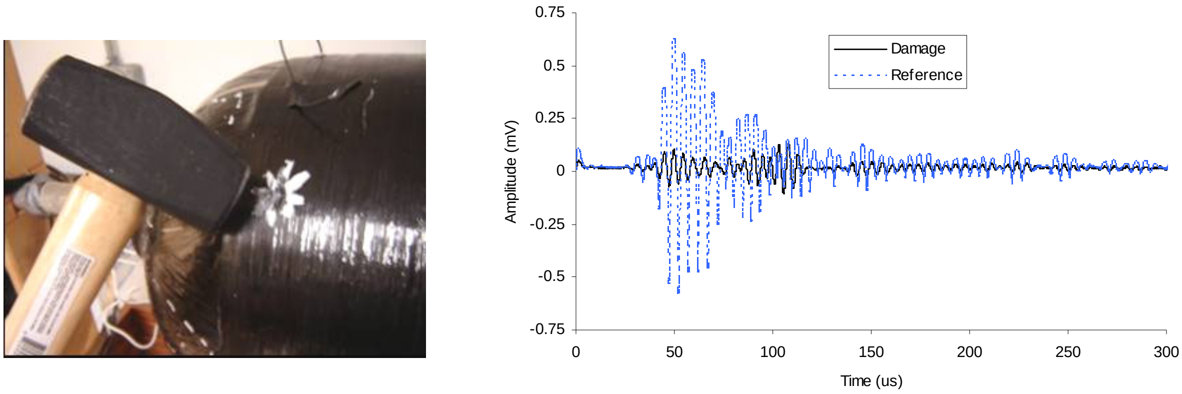



**Figure 5: Inflicting impact damage and pre/post wave form.**

The results of all the tests in unpressurized cylinders, which are summarized in Table 2, indicate correlation coefficients ranged from 0.93 to 0.44 depending on the type of damage.

A correlation coefficient of one corresponds to no change in the structure compared to the reference case. A correlation coefficient of less than one indicates the structure has changed due to damage. A software program was used to acquire pre- and post-damage data and to automatically calculate the correlation coefficient.

In both the axial and circumferential cases, impact damage resulted in the most significant change in signal. As well, the ultrasound was more sensitive to cuts (notches) oriented perpendicular to the direction of wave propagation than parallel. In the axial direction, for instance, the perpendicular cut (notch) data generated a correlation coefficient of 0.68 compared to 0.83 for the parallel case. Table 3 shows that as the size of cut damage increases, the correlation coefficient decreases.

**Table 2: Summary of defect detection results.**

| Defect Type | Defect Size | Frequency (kHz) | Correlation Coefficient |
|---|---|---|---|
| Axial hole | 3-mm diameter, 4.8-mm deep | 190 | 0.83 |
| Axial impact | 20-mm x 20-mm on surface | 190 | 0.44 |
| Axial parallel cut | 25 (L) x 2 (W) x 2 (D) mm | 190 | 0.83 |
| Axial perpendicular cut | 25 (L) x 2 (W) x 2 (D) mm | 190 | 0.68 |
| Circumferential hole | 3-mm diameter, 4.8 mm deep | 322 | 0.79 |
| Circumferential damage | 20-mm x 20-mm on surface | 322 | 0.69 |
| Circumferential parallel cut | 25 (L) x 2 (W) x 2 (D) mm | 322 | 0.93 |
| Circumferential cut | 25 (L) x 2 (W) x 2 (D) mm | 322 | 0.85 |

**Table 3: The effect of increasing damage size on correlation coefficient.**

| Cut Dimensions: L x W x D (mm) | Frequency (kHz) | Correlation Coefficient |
|---|---|---|
| 17 x 2 x 1 | 190 | 0.99 |
| 35 x 2 x 4 | 190 | 0.78 |
| 57 x 2 x 6 | 190 | 0.33 |

## 7 Discussion

This project investigated ultrasonic, resistive, and electromagnetic techniques for detecting damage in composite cylinders made of carbon fiber with aluminum liners. Ultrasonic techniques appear to have promise as a low-cost method of detecting damage using small piezoceramic disk sensors. Correlation coefficients comparing the tank structure before and after damage was inflicted ranged from 0.93 to 0.44 depending of the type and orientation of damage (cut, hole, impact). The next phase of work should focus on pressure cycling tests to ensure the durability of the sensor and the sensor adhesive, as well as developing a system for installation in a vehicle. It is also important to incorporate damage detection technology into Codes and Standards used to design storage cylinders for compressed gases.

**References**


[1] Intelligent control systems for fuel cell and natural gas vehicles, SRC Publication Number 11305-1E02, September 2002.

[2] Lung, B. A structural health monitoring system for composite pressure vessels. Thesis, University of Saskatchewan, 2005.

[3] Damage detection of high-pressure storage cylinders made of composite materials, SRC Publication number 11920-1C7, March 2007.

[4] M. Sulatisky et al. Dual-fuel hydrogen pickup trucks, WHEC16, Lyon, France, 13-16 June, 2006.

[5] Banks, H.T., D. J. Inman, D. J. Leo and Y. Wang. An experimentally validated damage detection theory in smart structures. Journal of Sound and Vibration, 191(5), pp859-890, 1996.

[6] Okafor, C., K. Chandrashekhara and Y. P. Jiang. Delamination prediction in composite beams with built-in piezoelectric devices using modal analysis and neural network. Smart Material Structure, Vol. 5, pp 338-347, 1996.

[7] Salawu, O.S. Detection of structural damage through changes in frequency: a review. Engineering Structures. Vol. 19,no. 9, pp718-723, 1997.

[8] Kunzler, Marley. Use of multidimensional fiber grating strain sensors for damage detection in composite pressure vessels. Internal Paper, Blue Road Research, BRR-2001, Vol. 4337, p 510, 2001.

[9] Lemistre, M. Electromagnetic localization of defects in carbon epoxy composite materials. Proceedings of SPIE, Vol. 3399.

[10] Balageas, Daniel, and Michael Lemistre. Hybrid Electromagnetic Acousto-ultrasonic Method for SHM of Carbon/epoxy Structures. Structural Health Monitoring. Sage Publications 2003, pp153-160.

[11] Kemp, R.M, N.J. Williamson, and P.T. Curtis. Development of Self Sensing Smart Composites Using Electrical Resistance Properties. Internal Publication, Structural Materials Centre, R50 Building, Farnborough, Hants.

[12] Scheuler, Ruediger, Joshi, P. Shiv, and Schulte, Karl. Damage Detection in CFRP by electrical conductivity mapping. Composites and Science Technology, Volume 61, pp921-930.

[13] Wang, Shoukai, Chung D.D.L., and Chung, Jaycee H. Self-sensing of damage in carbon fiber polymer-matrix composite cylinder by electrical resistance method. Journal of Intelligent Material Systems and Structures, Vol.17, January 2006.

# Self Ignition of Hydrogen by Various Mechanisms

**M. Royle**, **J. Gummer**, **P. Hooker**, **D. Willoughby**, **J. Udensi**, Health and Safety Laboratory, Buxton, Derbyshire, SK17 9JN, UK

## 1 Introduction

With the inevitable transition to some form of hydrogen based economy, spontaneous or self ignition of hydrogen is clearly important(1). A number of mechanisms have been suggested which may account for this phenomenon. This paper reports the results of studies to investigate four possible suggested reasons for this behaviour:

Sudden adiabatic compression in shock wave formation.

Charging of a hydrogen jet leading to electrostatic ignition

Charging of particles within the hydrogen stream leading to electrostatic ignition

Ignition of a premixed volume of hydrogen/air by corona discharge

Health and Safety Laboratory have performed experiments in order to attempt to define conditions under which hydrogen can apparently self ignite and to confirm which mechanisms may account for this behaviour.

Experiments were performed to investigate:

- Ignition by adiabatic compression due to boundary layer failure.
- The current and polarity necessary to ignite pre-mixed clouds of hydrogen/air by corona discharge.
- The charge produced by a hydrogen jet emerging into free air both with and without entrained particles within the jet.

## 2 Literature Review

The first part of this project was a literature review, published separately (Gummer and Hawksworth 2007). The design of these experiments was based on Astbury and Hawksworth 2005, Golub et al 2006 and Dryer et al 2007. In particular the work of Dryer gave a starting point for the experiments to investigate the ignition of sudden releases of compressed hydrogen to atmosphere. In addition to being significant as probably the first piece of experimental work to demonstrate ignition of releases into 'normal' everyday type environments, it was important as it also identified the influence of downstream obstructions on the propensity to ignite.

## 3 Experimental Programme Phase 1 – Diffusion Ignition Tests

The work in part of the programme involved tests using a bursting disk assembly and down-stream geometry similar to that used by Dryer; a photograph of the assembly is shown at figure 1. The fitting marked A in the photograph was specially manufactured to take a Kistler pressure transducer so that the pressure profile in the cavity immediately downstream of the bursting disk could be recorded as the disk burst. The fitting to the right of A is the top of the bursting disk assembly, B is a ½ inch NPT socket and C is a restricted pipe fitting. The hydrogen flow is from right to left. All the experiments were performed outside with the hydrogen released to open atmosphere. The hydrogen for the tests was supplied from HSL's 1000 bar experimental hydrogen facility; a schematic of the set up is shown at figure 2.

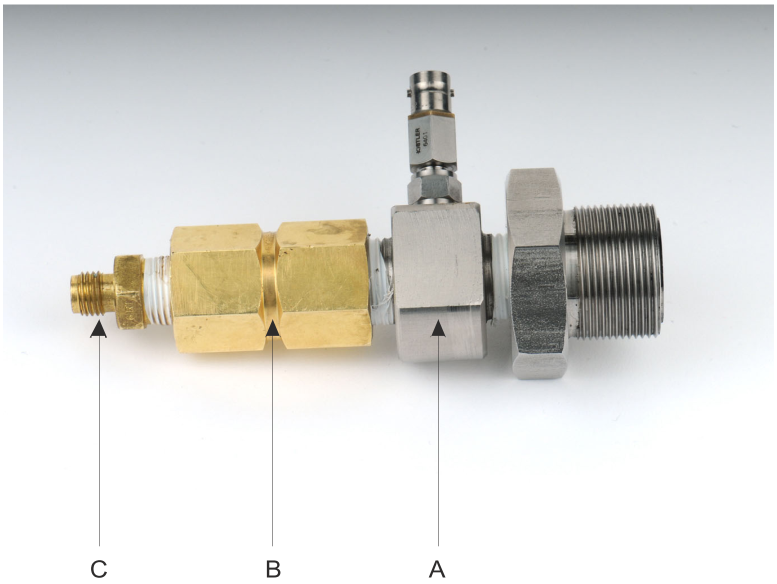



**Figure1: Geometry downstream of bursting disk.**

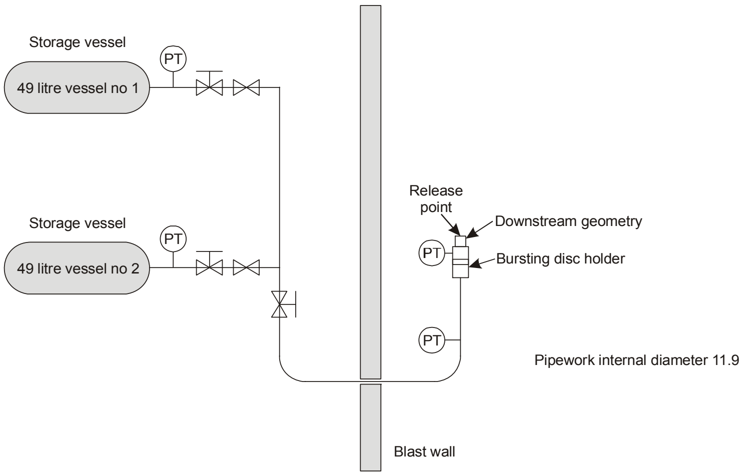



**Figure 2: Simplified schematic of the spontaneous ignition high-pressure $H_2$ test facility.**

A total of 85 tests were carried out using variations on downstream geometries and pressures. The lowest disk burst pressure at which an ignition was obtained was 35.5 bar; this corresponded to a transient cavity pressure (downstream of the bursting disk) of 28.6 bar. A plot of cavity pressure against burst pressure for ignitions and non-ignitions is shown at figure 3.

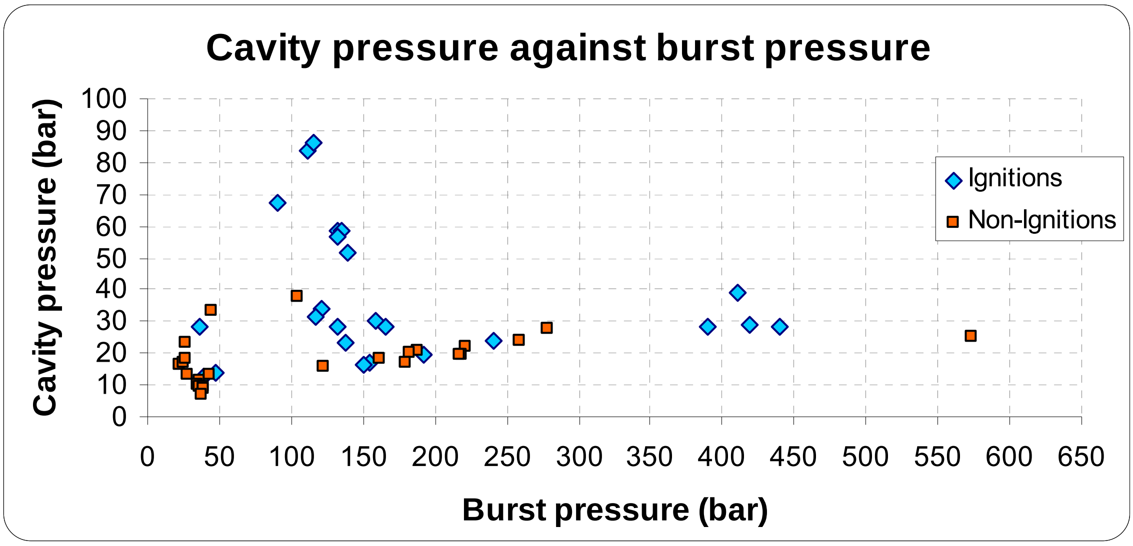



**Figure 3: Plot of cavity pressure against burst pressure for cases of ignition and non-ignition.**

### 3.1 Experimental programme Phase 2 part 1– Ignition of hydrogen/air mixtures by generated corona discharge

A cylindrical vessel of dimensions (1.22m dia × 1.70m long) was used to investigate the conditions under which $H_2$-air mixtures may be ignited by corona discharges. The vessel was fitted with explosion relief consisting of physically weak electrically conducting plastic film that was physically and electrically bonded to the vessel to avoid potential spark and brush discharges. The vessel was enclosed by a Faraday cage formed by an iron wire mesh supported on a frame to block out external electric fields. Despite this very small currents were detected from the vessel (about 100 pA), due to dust impingement.

Attempts were made to ignite known concentrations of $H_2$-air mixtures by inducing a corona discharge within the gas mixture. The $H_2$ concentrations used in the tests were within a range around the concentration for which the lowest spark ignition energy is observed (i.e. 28% v/v) with a concentration of $H_2$ between 26% v/v and 33% v/v in air being employed. Figure 4 shows a schematic of the experimental arrangement used for these tests.

## 4 Corona Wire Arrangement

It was considered unlikely that in a well-earthed $H_2$ handling system a situation would arise where two conducting items were close to each other but at significantly different potentials. Therefore, initially, the wire was positioned centrally in the vessel, using the vessel walls (approximately half a metre away) as the “earthed” electrode. When no ignitions occurred with this arrangement, an electrode (a metal plate electrically bonded to the vessel) was placed approximately 30 mm away from the corona point to generate higher corona currents.

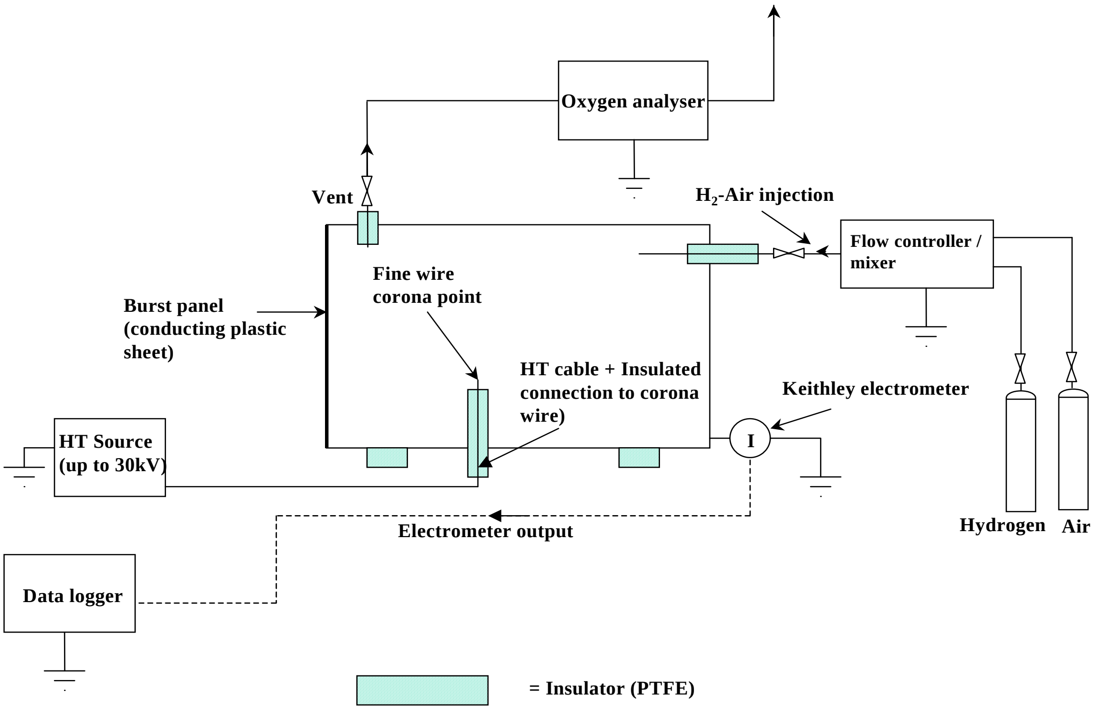



**Figure 4: Schematic of the experimental arrangement used for ignition of H2-Air mixtures from generated corona discharges.**

Summarising the results from the generated corona discharge experiments, the only condition that resulted in ignition of the $H_2$-air mixtures was with a positive potential of > 20 kV applied to the wire and with a 30 mm gap between the wire and the earthed electrode, the discharge having a current of approximately 150 µA. It is possible that the corona had transitioned into an arc by this stage. This ignition was repeated with $H_2$-air gas mixtures of 28% v/v and 30% v/v of $H_2$. No ignitions were obtained with a negative potential up to –28 kV and –290 µA (the maximum used in the tests).

## 4.1 Experimental programme Phase 2, part 2– Investigation of corona discharges during high-pressure $H_2$ releases

Experiments were performed to investigate whether the release of pressurised $H_2$ could result in incendive corona discharges and, ultimately, ignition of the released $H_2$.

The electrostatic field was measured during horizontal high pressure hydrogen releases into air both for pure hydrogen and for hydrogen with dust added.

An electrostatic field mill was positioned just below a stainless steel pipe, which had a 2” nominal bore and length of 2.5 m, to measure the electric field in the direction of the $H_2$ release. Fine wires (0.38 mm diameter nichrome) were placed at various positions in an attempt to promote corona discharges.

$H_2$ was released from the high-pressure $H_2$ facility, for a duration of four seconds from a starting nominal pressure of 200 barg (i.e. typical pressure for commercially available cylinders). The released gas was directed into a stainless steel pipe with 2-inch nominal bore and length of 2.5 m. In some cases, powder was placed inside the pipe to be dispersed by the $H_2$ flow in order to increase the electrostatic effects. Two different dusts were used: a plastic powder consisting of coarse (1-2 mm) and fine particles of a few hundred microns, and a fine (ca. 10 µm) iron (III) oxide powder (rust).

The amount of charge on the dispersed dust was inferred by measuring the charge (of opposite polarity) transferred to the pipe. The charge was measured using two methods: a JCI178 charge meter for charge of <20 µC, and by measuring the potential on a 1 µF capacitor attached to the pipe for charges > 20 µC. No corona discharges sufficient to ignite hydrogen air mixtures were measured with dust dispersions of up to 160g in hydrogen releases from 200 bar storage. A schematic of the experimental arrangement is shown in figure 5.

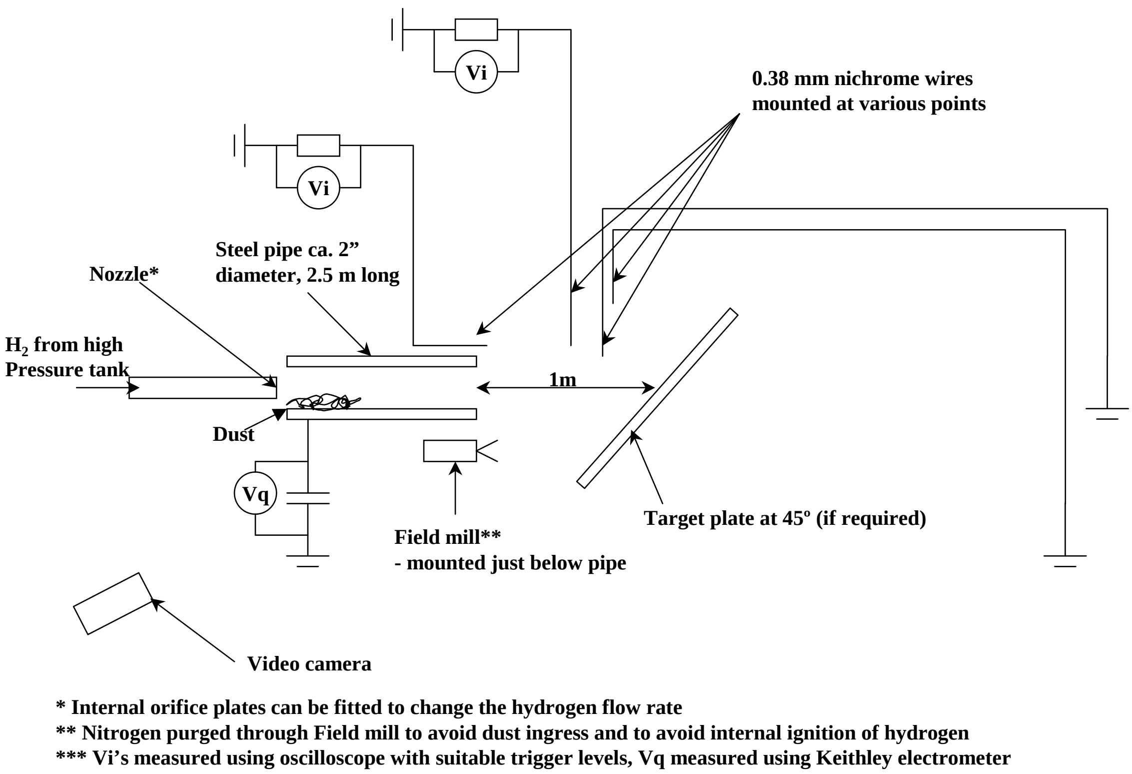



**Figure 5: Schematic of the experimental arrangement used for investigating corona discharges during high-pressure $H_2$ releases.**

## 5 Conclusions

For the first phase of experimental programme, the following conclusions were made for diffusion ignition tests involving bursting discs and pipe work downstream of a boundary failure.

- No ignitions were observed below a cavity pressure of 8.8 barg.
- Ignitions always occurred above a cavity pressure of 27 barg.
- Releases of $H_2$ to atmosphere with no restrictive and reflective downstream geometry present resulted in no ignitions up to a burst pressure of 831 bar.

- Tests which included reflective downstream geometry always produced ignitions at disc burst pressures above 260 bar.
- The lowest burst pressure for ignition was 35.5 bar with a reflective geometry configuration and vent area of 17.3 $mm^2$ and soft ductile bursting discs were less likely to produce an ignition than a non-ductile disk.
- Whether ignition occurs appears to be related to the rise time of the pressure pulse produced by the disc failing. The rise time is related to the burst pressure and also the extent of downstream constriction after the bursting disc.
- When $H_2$ leaked into cavity before a burst, no ignitions occurred.
- No ignitions were observed when weakened pipes were used for open geometry tests at pressures of up to 417 bar.

In the second phase of experimental programme the following conclusions for tests involving corona discharges were attained.

- $H_2$-air mixtures were ignited by corona discharges generated by raising a fine wire to a high potential.
- Ignitions occurred with positive corona discharges at a current of approximately +150µA and potential of +20kV for a wire point and plate electrode system with a 30mm separation.
- No ignition was observed with negative currents of up to approximately –290 µA and potential of –28 kV.
- Dispersion of dusts up to 160g with $H_2$ released from 200 barg did not appear to generate hazardous electric fields, in terms of incendive corona discharges.
- Ignition can be produced by corona discharges of the type that might be produced where fine points may be at a potential of several tens of kV above the surrounding atmosphere. Such situations could be expected at the top of tall vent stacks (Bradburn, and McBrien 1983, ICI 1977, Astbury 2007), tens of metres above ground, in the presence of large atmospheric electric fields (e.g. during snow fall). Such incendive corona discharges appear to be unlikely in horizontal releases of $H_2$ close to ground level.

### Acknowledgements

This publication and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

### References

[1] Astbury, G. R., and S. J. Hawksworth, 2005, Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms: Proceedings of International Conference on Hydrogen Safety.

[2] Astbury, G. R, 2007. Venting of low pressure hydrogen gas - A critique of the literature. Process safety and environmental protection, 85, 289-304.

[3] Bradburn, F., and D. McBrien, 1983, Discussion of Hydrogen Vent Ignitions, Technical Visit report No. TVR194.

[4] Dryer, F. L., M. Chaos, Z. Zhao, J. N. Stein, J. Y. Alpert, and C. J. Homer, 2007, Spontaneous Ignition of Pressurized Releases of Hydrogen and Natural Gas into Air: Combustion Science and Technology, v. 179, p. 663-694.

[5] Golub, V. V., T. V. Bazhenova, M. V. Bragin, M. F. Ivanov, and V. V. Volodin, 2006, Hydrogen Auto-Ignition During Accidental or Technical Opening of High Pressure Tank: Proceedings of the 6th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions.

[6] Gummer, J., and S. H. Hawksworth, 2007, Spontaneous Ignition of Hydrogen: Literature Review, Health and Safety Laboratory.

[7] ICI, 1977, Thunderclouds, Lightning, Corona Discharges and the Ignition of Hydrogen Vents by Static, ICI Mond Division Report No. MD18641.

# Simulation of Hydrogen Releases from Fuel-Cell Vehicles in Tunnels

**William G. Houf**, **Greg H. Evans**, **Scott C. James**, Sandia National Laboratories, Livermore, USA
**Erik Merilo**, **Mark Groethe**, SRI International, Menlo Park, CA USA

## 1 Introduction

An important issue concerning the safe use of hydrogen-powered vehicles is the possibility of accidents inside tunnels resulting in the release of hydrogen. Releases of hydrogen from high-pressure gaseous storage tanks on vehicles are designed to occur only for conditions where a heat source, such as a fire, is present to actuate the thermal pressure relief device (TPRD). It is presumed that this heat source also serves as an ignition source that will immediately burn the released gas and a jet flame will ensue. A highly unlikely scenario is the case where the released hydrogen remains unignited for some period of time followed by a possible ignition.

## 2 Risk Analysis Considerations

A true risk assessment of this accident scenario would involve a two-part study with a determination of the frequency of occurrence of the specific accident and an evaluation of the severity of the consequence from the incident. In the case of the frequency evaluation, there is no statistical data for hydrogen releases from vehicles and hence any determination of the frequency of occurrence has a high degree of uncertainty. Some data is available for gasoline-powered vehicles in tunnels, and as a first approach it can be assumed that the accident rate for hydrogen vehicles in tunnels might be similar. For a typical road tunnel in a highly populated area there are approximately $35 \times 10^6$ vehicle transits per year with approximately 720 crashes per year and only 12 vehicle fires per year (most of which are initiated by mechanical or electrical malfunctions). Based on this data the fraction of tunnel transits resulting in a vehicle fire is approximately $3 \times 10^{-7}$ fires/transit. Assuming an average vehicle makes between 1 to 100 tunnel transits per year, then the estimated frequency of the vehicle being involved in a tunnel fire would range from $3 \times 10^{-7}$/yr to $3 \times 10^{-5}$/yr. The estimated fire frequency contribution from vehicle crashes is $2 \times 10^{-6}$/yr. Not all tunnel fires involving hydrogen vehicles may induce TPRD activation and subsequent hydrogen ignition. From a risk point of view, the first consideration is that the risk to individuals from hydrogen vehicle accidents in tunnels does not substantially increase their existing risk from everyday life. In the United States the average individual fatality risk from all types of accidents (from everyday life) is approximately $5 \times 10^{-4}$/yr (LaChance et al., 2009). Recognizing that only a fraction of hydrogen vehicle fires will result in TPRD releases, hydrogen ignition, and a subsequent fatality, the individual fatality risk from hydrogen vehicle fires in tunnels is estimated to range between $2 \times 10^{-7}$/yr to $3 \times 10^{-5}$/yr and does not significantly increase the level of individual risk to the public.

## 3 Consequence Analysis

Because hydrogen vehicle PRDs are thermally activated devices, they would most likely be activated by a fire engulfing the high-pressure hydrogen storage tank, which would serve to ignite the flammable gas upon release. Presumably, ignition of the flammable gas would occur almost instantaneously upon exiting the vent pipe, resulting in a jet flame rather than a deflagration through a premixed hydrogen and air mixture which could result in overpressure. In a scenario involving TPRD activation, flammable gas venting to the environment must be considered and the time delay prior to ignition becomes a parameter. Thus, in performing consequence analysis of a hazardous gas release, which is an important part of risk assessment, knowledge of the time-dependent transport of flammable gas from the vent pipe of a vehicle PRD during the blow-down of the high-pressure tank is important.

Sandia's computational fluid mechanics code, FUEGO (Moen et al., 2002), was used to perform simulations of hydrogen fuel-cell vehicle (HFCV) TPRD releases inside ventilated tunnels. For these simulations, high-pressure hydrogen gas was vented simultaneously from three separate onboard tanks through three separate TPRD vents located on the bottom of the HFCV. The vents were approximately 15cm above the roadway and the hydrogen flow was directed downward. Each tank held approximately 1.67kg of hydrogen at an initial pressure of approximately 70MPa. Predictions of the evolution of flammable hydrogen/air gas volume inside the tunnel resulting from the blowdown were performed by first calculating the steady air flow within the tunnel (and exhaust plenum for a transversely ventilated tunnel) and then releasing the flammable gas into the tunnel air flow through the openings representing the three TPRD vents. The transient nature of the tank blow downs was modeled with the Sandia developed compressible network flow analysis code, NETFLOW (Winters, 2001, 2009), and used to develop transient boundary conditions for the TPRD vents.

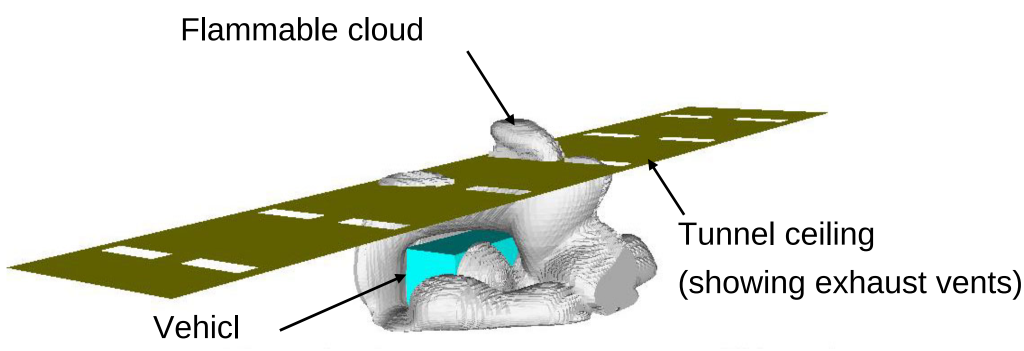



**Figure 1: Simulation of flammable hydrogen cloud (4% - 75% mole fraction) around vehicle 2 seconds into three TPRD release in a transversely-ventilated tunnel (ventilation rate of 15 air changes per hr).**

Figure 1 shows the evolution of the flammable hydrogen cloud (4% - 75% mole fraction) around the vehicle in a transversely-ventilated tunnel 2 seconds into the 3 TPRD release. Figure 2 shows flammable volumes of hydrogen from the vehicle release for various ventilation rates in a transversely-ventilated tunnel. Results indicate that increasing the ventilation rate reduces the peak flammable volume and also significantly reduces the time required for dilution below the lower flammability limit (4% mole fraction) of hydrogen.

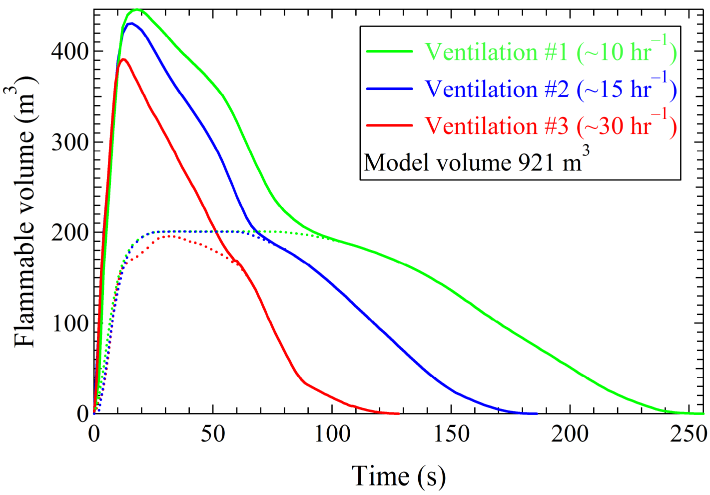



**Figure 2: Simulation results showing evolution of flammable hydrogen volume (4% - 75% mole fraction) from a vehicle with three simultaneous TPRD releases in a transversely-ventilated tunnel for ventilation rates of 10, 15, and 30 air changes per hour. Solid lines are total flammable volumes (both tunnel and ventilation plenum) and dashed lines are flammable volumes in plenum only.**

Ignition overpressure simulations for the hydrogen vehicle releases in the transversely-ventilated tunnel were also performed. These simulations were based on flammable cloud volumes and concentrations extracted from the FUEGO dispersion calculations under nominal ventilation conditions (15 air changes per hour). A FLACS (2009) model of the transversely-ventilated tunnel and vehicle was developed and three-dimensional concentration distributions of the flammable hydrogen cloud volume were extracted from the FUEGO simulations and read into the FLACS model. FLACS was then used to perform a transient simulation of ignition of the cloud and the associated overpressure generated by a rapid deflagration wave propagating across the cloud. The time delay between the beginning of the TPRD release and ignition and its effect on the deflagration overpressure were also studied. Figure 3 shows simulations of the peak overpressure on the tunnel walls for ignition under the vehicle 2 seconds after the beginning of the TPRD release. Figure 4 shows simulations of the transient variation of the pressure and impulse on the tunnel sidewalls adjacent to the vehicle for the case where ignition occurs 2 seconds after the beginning of the TPRD release. Figure 5 shows the peak ignition overpressures observed in the simulations for different ignition delay times (time between beginning of TPRD release and ignition) and ignition locations.

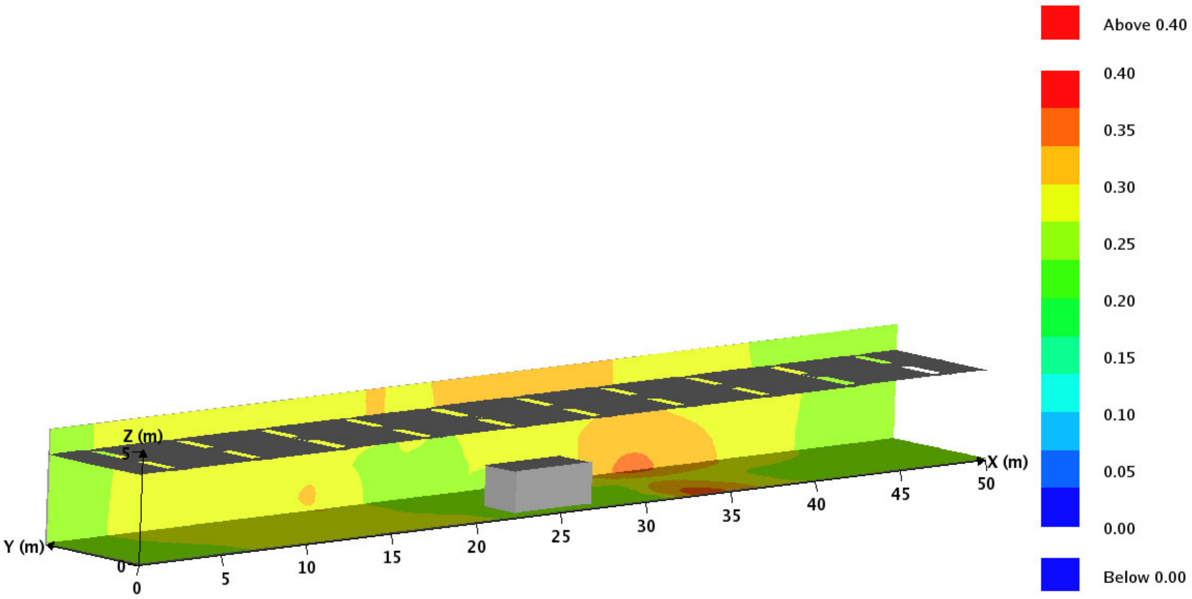



**Figure 3: Simulation of peak ignition overpressures (barg) on transversely-ventilated tunnel walls for ignition under the vehicle 2 seconds after the beginning of the TPRD release.**

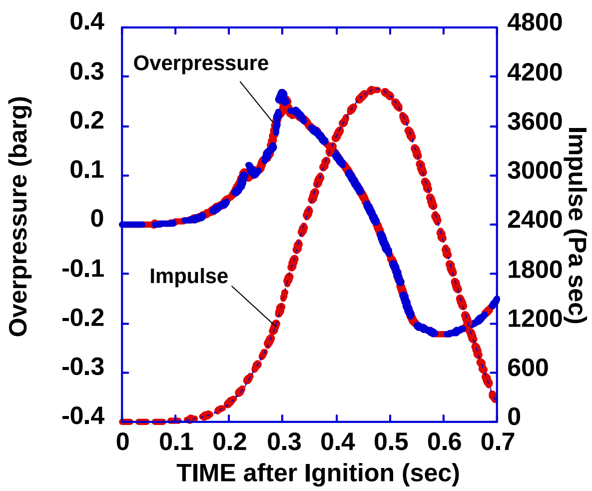



**Figure 4: Simulation results showing transient variation of ignition overpressure and impulse on transversely-ventilated tunnel sidewalls (at location of vehicle) for ignition of the hydrogen cloud 2 seconds after the beginning of the TPRD release.**

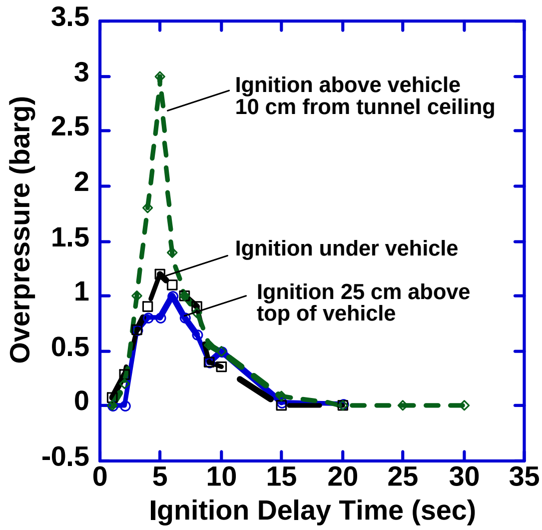



**Figure 5: Simulation results showing peak ignition overpressure in the transversely-ventilated tunnel for different ignition delay times (time between beginning of TPRD release and ignition) and locations.**

## 4 Experimental Validation of Model Simulations

A set of experiments was performed in a scaled tunnel test facility at the SRI Corral Hollow Experiment Site (CHES) to provide model validation data for the simulations (see Figure 6). The SRI tunnel test facility has a cross-sectional area that is approximately 1/2.53 that of the full-scale transversely-ventilated tunnel. As part of these experiments appropriate scaling factors (Hall and Walker, 1997) were determined to create a set of scaled-tunnel tests that resembled as closely as possible the full-scale tunnel simulations. The scaled hydrogen mass released in the test was related to the full-scale hydrogen mass released by the volume ratio $(1/2.53)^3$. The time for the scaled mass release was related to the time for full-scale mass release by using the Froude number and dimensionless time. The initial tank pressure for the experiments was 13.79 MPa and the tank volume was chosen so that it would hold the scaled mass of hydrogen. The release diameter was then designed to match the scaled mass flowrate versus scaled time tank blowdown curve from the full-scale release.

Measurements were made of the hydrogen concentration, flame speed, and ignition delay overpressure in the scaled tunnel resulting from the release produced by activation of three simulated PRD vents on the bottom of the scale-model vehicle. As part of the work a FUEGO dispersion model and FLACS deflagration model of the test tunnel and vehicle geometry were developed. These models were used prior to the tests to estimate the placement of concentration and pressure sensors in the tunnel test geometry and to determine the amount of expected overpressure from ignition of the hydrogen releases. Figure 7 shows a simulation of the flammable hydrogen cloud (4% to 75% mole fraction) in the SRI test tunnel one second after the beginning of the release. Pretest FLACS ignition deflagration simulations of the test tunnel geometry using three-dimensional concentration maps from the FUEGO dispersion simulations indicated that the maximum overpressure would be approximately 0.5 barg and that a peak in the overpressure would occur with increasing ignition delay time as observed in the full-scale tunnel simulations (see Figure 5). Figure 8 shows a comparison of the peak overpressures observed in the experiment for different ignition delay times as compared to the FUEGO/FLACS model simulations. The ignition overpressure simulations are found to be in good agreement with the experimental data.


**Figure 6: Photograph and cross-sectional area sketch of scaled tunnel and vehicle at SRI Corral Hollow Experiment Site (CHES).**

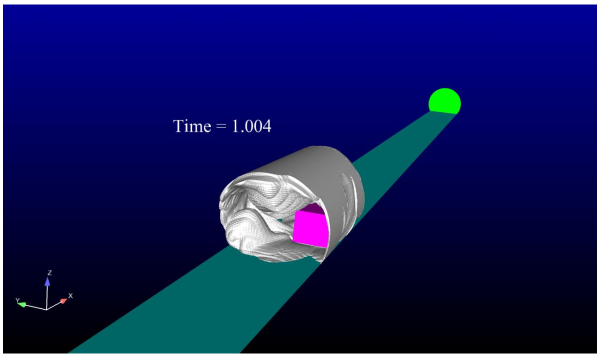



**Figure 7: Simulation of flammable hydrogen cloud volume (4% to 75% mole fraction $H_2$) around the vehicle in the SRI test tunnel one second after the beginning of the release.**

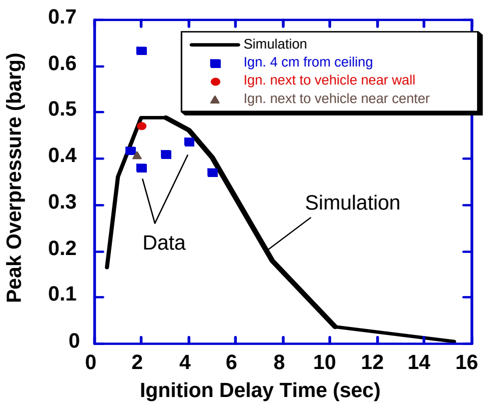



**Figure 8: Comparison of measured peak ignition overpressure in the SRI test tunnel facility with results from FUEGO/FLACS model simulations.**

Figure 9 shows predicted and measured hydrogen mole fraction at two locations within the scaled tunnel at the tunnel ceiling. Both predicted and measured hydrogen mole fraction increase rapidly from 0 to approximately 0.4 within 1 second of the start of the release at 1.5 m along the tunnel axis from the center of the vehicle (red curve and symbols). At approximately 2 seconds after the start of the release the predicted and measured hydrogen mole fraction increase from 0 to approximately 0.3 at 3.0 m from the center of the vehicle along the tunnel axis (black curve and symbols). Qualitatively the predicted and measured values agree and the concentration behavior is expected. At larger distances from the release, there is a longer delay before the detection of hydrogen and the magnitude of the hydrogen mole fraction is reduced due to dispersion. The agreement between predicted and measured values is reasonable.

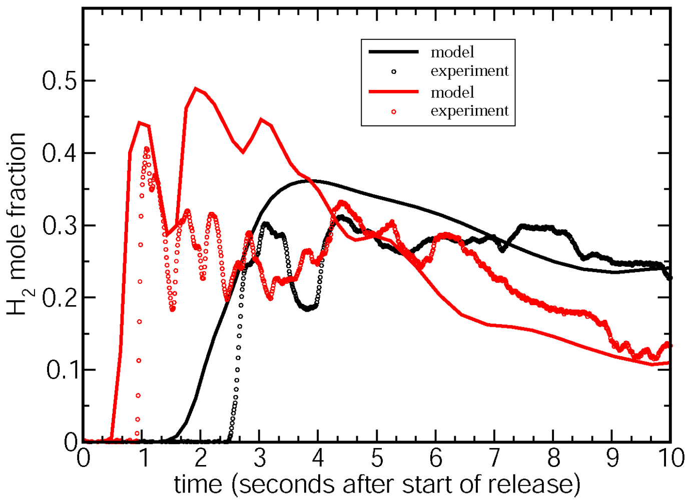



**Figure 9: Comparison of time evolution of predicted and measured $H_2$ mole fraction at two locations on the centerline at the ceiling in the scaled tunnel: red curve and circles 1.5 m from vehicle center; black curve and circles 3.0 m from vehicle center.**

## 5 Summary and Conclusions

Simulation results for a hydrogen fuel-cell vehicle in a full-scale tunnel have been performed for the case where hydrogen gas is vented from the vehicle as a result of thermal activation of the pressure relief device (PRD). The same modeling approach used in the full-scale tunnel modeling was validated in a scaled model by comparing simulated results with measured results from a series of scaled-tunnel test experiments performed at the SRI Corral Hollow test facility. Results of the simulations were found to be in good agreement with the experimental data. Finally, a rudimentary risk analysis indicated that the level of potential risk from hydrogen vehicles accidents involving thermally activated PRDs in tunnels does not appear to significantly increase the current level of individual risk to the public from everyday life.

**Acknowledgements**

The authors wish to acknowledge Jeff LaChance for his helpful discussions regarding the risk analysis considerations in the paper. This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program under the Codes and Standards subprogram element managed by Antonio Ruiz.

**References**

[1] FLACS Version 9.1 User's Manual, GEXCON, Bergen, Norway, November 2009.

[2] Hall, D.J., Walker, S., "Scaling Rules for Reduced-Scale Field Releases of Hydrogen Fluoride," Jour. of Hazardous Materials, Vol. 54, pp. 89-111, 1997.

[3] LaChance, J., Houf, W., Middleton, B., Fluer, L., "Analysis to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards," Sandia Report SAND2009-0874, March 2009.

[4] Moen, C.D., Evans, G.H., Domino, S.P. and Burns, S.P., "A Multi-Mechanics Approach to Computational Heat Transfer," Proceedings 2002 ASME Int. Mech. Eng. Congress and Exhibition, New Orleans, IMECE2002-33098, November 17-22, 2002.

[5] Winters, W.S., "A New Approach to Modeling Fluid/Gas Flows in Networks," Sandia National Laboratories Report SAND20001-8422, July, 2001.

[6] Winters, W.S., "Implementation and Validation of the NETFLOW Porous Media Model," Sandia National Laboratories Report SAND2009-6838, October 2009.

# Hydrogen Safety: R&D Work in the Horizon Hydrogen Energie Program

**Sidonie Ruban**, **Simon Jallais**, **Deborah Houssin**, **Valérie Naudet**, **Claire Weber**, Air Liquide, Jouy-en-Josas, France
**Jérôme Daubech**, **Christophe Proust**, INERIS, Verneuil-en-Halatte, France
**Alain Bengaouer**, CEA, Gif-sur-Yvette, France

## 1 INTRODUCTION

The energy industry is undergoing an important transformation (global warming, dependence of the energy supply, depletion of energetic resources); our societies will have to develop solutions that are sustainable and more environmentally-friendly. In the frame of those global challenges, hydrogen can play a key role in the development of new energy alternatives. As a carrier that is compatible with other types of energies, it can be produced from a wide variety of sources including renewable, while presenting unique storage options and, combined to a fuel cell, efficiently produces electricity with zero direct pollution.

Energy and environment being major growth drivers, Air Liquide decided to lead the Horizon Hydrogène Energie (H2E) program. This ambitious French program represents a global investment of 190 million Euros over 7 years in research and technology development and federates 19 partners in order to implement new industry for hydrogen energy.

Competitive solutions are already available and Air Liquide deploys them onto four main “early” markets – off-grid sites, backup power, special vehicles and mobile energy – with a fully dedicated supply chain as illustrated in Figure 1. In order to establish a market-receptive environment for hydrogen-based products and have development/modification of relevant codes and standards that will ensure the safe operation, handling and use of hydrogen technologies, it is essential to implement a specific safety strategy during the product design phase. A scientific basis for providing realistic risk assessment and possible mitigation means is required to reach the safety objectives.

A comprehensive R&D effort has been launched in the frame of the Horizon Hydrogène Energie (H2E) program for assessing the safety of hydrogen-based systems. It is conducted in collaboration with French research institutes (CEA, INERIS) and French academic laboratories (LCD Poitiers and PRISME Bourges).

As part of the program, investigation on safety aspects covers most areas of hydrogen distribution, storage under high pressure and use in fuel cells. It aims at providing experimental and numerical results to understand hydrogen behaviour in different accident scenarios – from leakage to dispersion, ignition, and explosion – and to understand the behaviour of high pressure full composite hydrogen storage to mechanical and thermal aggressions. Emphasis is given to risk mitigation strategies. The paper presents the work program and introduces methodology and early results.


**Figure 1: Overview of hydrogen early markets.**

# 2 Presentation of the Work Program

## 2.1 Release flow rate and shape in real-leak conditions

The objective of this task consists in experimentally measuring leak rates associated to hydrogen fittings. Knowledge of this value is crucial for risk assessment as it is used as a source term. In risk assessment studies, the leak is generally modelled as a release of gas through a circular hole. However, on the basis of Air Liquide long experience on hydrogen production and distribution technologies, this type of approach to characterize leak is too conceptual and conservative. In the current task, leak flow rates generated by expectable and accidental fitting solicitations will be measured and characterised for two types of commercialized fittings (see Figure 2):

- double ferrule fittings with setting of ferrules and sealing on the conical ferrule (like Swagelok or Sagana fittings),
- and “cone and thread” fittings with thread collar and sealing on a cone (like Sitec or Autoclave fittings).

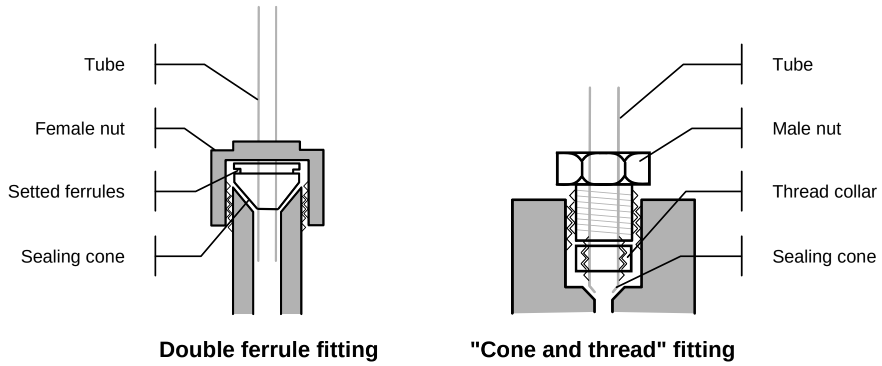



**Figure 2: Schemes of the selected fittings.**

It should be noticed that these two fitting types are classically used at high pressure (200 bar), even with references at pressures near 1000 bar for “cone and thread” fittings.

A reliability approach was used to determine all causes of leak for a fitting. Fault trees, taking into account the lifetime were built for the two types of fittings. Three main causes were identified: material defaults, assembly faults and solicitations in use. Fault trees also showed that problems due to material and assembly are mainly solved using procedures (double checking for example). Real-life solicitations will be experimentally reproduced in order to quantify their level of leak (see Figure 3).

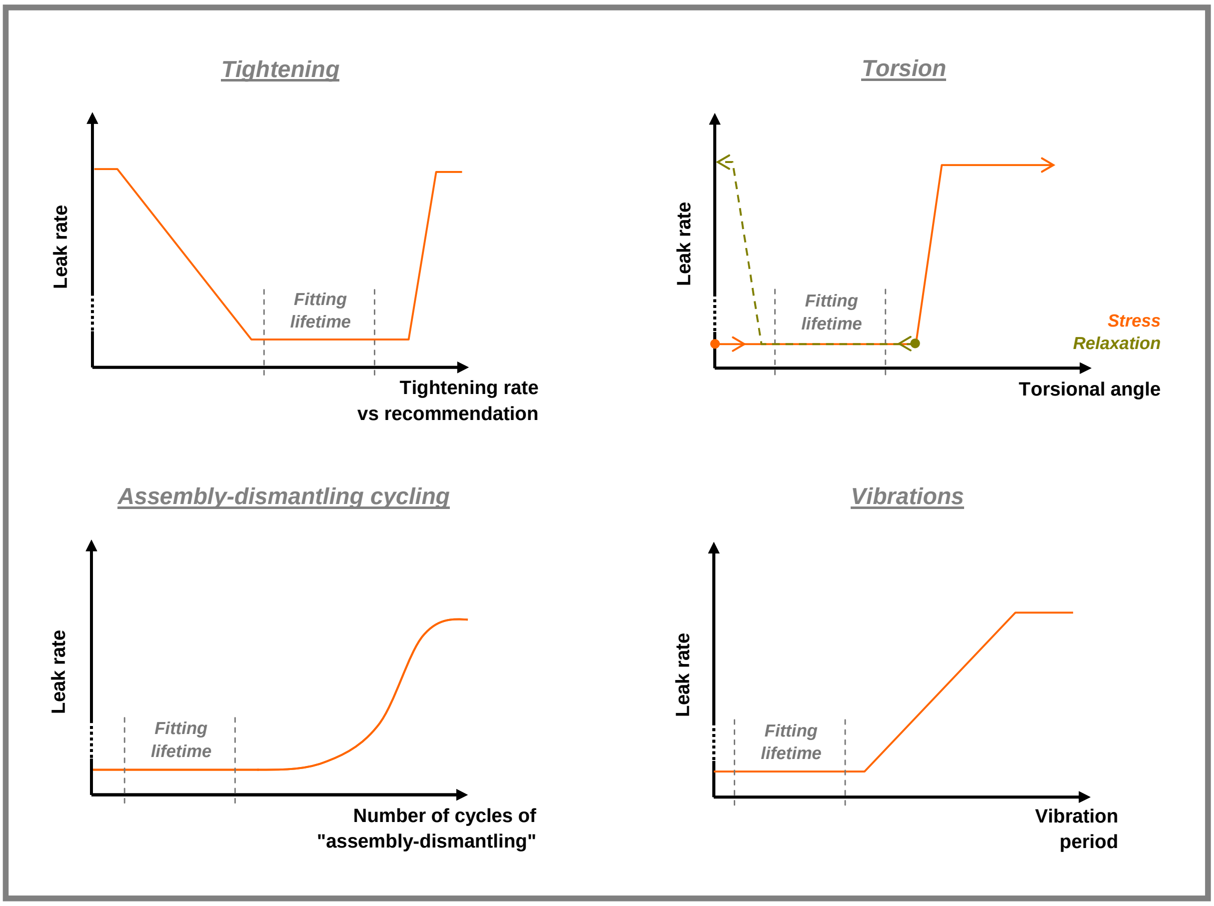



**Figure 3: Experimental planned tests.**

This type of experiments has been also performed in Drive French national project [1] at moderate pressures (< 35 bar) and for pipe fittings ¼’’ mainly. It shows that these fittings have a very low leak rate in normal conditions (< $10^{-3}$ $cm^3.s^{-1}$) but could be an important source of release in case of insufficient tightening or with a default on the fitting (leak rate up to 300 $cm^3.s^{-1}$). Future works in H2E project will extend knowledge on this thematic.

Important outcome of this study will be a better definition of fittings limits of use and of maintenance frequency to ensure an appropriate level of safety. Guidelines for design of the hydrogen-based systems next generation could also be issued.

## 2.2 Dispersion, gas build-up and deflagration in confined area

In H2E project, a risk informed safety approach is adopted: mitigation objectives are defined with regards to foreseeable deviations or accidental events in function of their expected likelihood:

1. For expectable releases, the objective is to avoid the development of an explosive atmosphere in the considered confined area. This is mainly achieved by ventilation.
2. Less likely accidental releases may have effects, but not to the extent of producing injury (e.g. a flammable mixture may be acceptable if its ignition will produce limited effects).

The task aims to define practical means for meeting these objectives.

Background works have been performed in sealed confined configurations [2,3,4]. Within H2E projects, experiments will be performed in CEA Garage facility (see Figure 4) with a specific focus on natural ventilation (through one or two openings, with and without wind effects) and forced ventilation configurations. Another task is devoted to hydrogen dispersion through a first confinement (which is played by hydrogen objects structure) in a second confinement (i.e. the room where $H_2$ object is located).


**Figure 4: CEA Garage facility (source: CEA).**

Experiments on hydrogen-air deflagration (so-called vented explosion) will be performed by INERIS to define design rules of overpressure venting which will have to be a trade-off between internal (overpressure in the confined volume) and external (flame and overpressure outside of the volume) effects. These experiments will also be used to validate CFD combustion codes and to develop engineering predictive tools.

In the project, influence of main parameters characterizing combustion regime, and pressure and thermal loads – mixture composition and mixture distribution (uniform/stratified mixtures); vent size, inertia, opening pressure; degree of obstruction and obstacle(s) configuration – will be investigated both experimentally and numerically.

# 3 Cylinder Safety

In the hydrogen energy applications, due to global energetic density considerations, hydrogen is stored at high pressure (up to 700 bar) in fully wrapped carbon fibers composite cylinders. These cylinders can undergo thermal and mechanical aggressions.

Thermal aggressions

Thermal aggressions can be generated by a generalized fire, a localized fire (like an impacting jet fire) or an exposure to an excessive temperature (e.g. cylinder in a smoke layer or in a room neighbouring a fire). In order to avoid cylinder burst in the fire, cylinders can be equipped with a TPRD (Thermally activated Pressure Relief Device) [5] releasing hydrogen when its local temperature is excessive considering cylinder materials (typically T > 110°C). However, TPRD produce a hazardous hydrogen flame (more than 2 m) and are not an efficient solution in case of local thermal aggression due to their local measuring capacity. As a consequence, H2E program plans to experimentally study specifically designed TPRD leading to short flame (INERIS) and to evaluate protective thermal layer solutions as mitigation strategies (LCD and INERIS).

Some technologies have been identified – e.g. intumescent painting, thermal barrier and wood-based protection – and will be experimentally tested by INERIS in real pool fire configurations for H2E project. Response to heat radiation of the composite, with and without protective layer, will be also studied on the basis of cone calorimeter experiments (LCD).

Mechanical aggressions

Cylinders manipulation in Air Liquide supply chain and during use by the customer can induce exposure to different mechanical aggressions. These aggressions can be mainly a vehicle crash (mobile energy), a vehicle impact (forklift for example) and a drop (e.g. from a delivery truck). Aggression mechanisms characteristics (i.e. velocity, impact energy, impact area, shape of the impinger) which could generate an immediate cylinder failure are unknown. Numerous studies on impact on composite structures have been published since 1990 [6,7]. Unfortunately, very few works are dedicated to impact on cylinder or curved structures. These studies highlighted three damage mechanisms leading to a decrease of the mechanical properties of a composite structure: matrix cracking, fiber rupture and delamination. H2E Safety program will experimentally determine the limits of mechanical aggressions leading to a cylinder burst. On this basis, the need of a mechanical protection on the cylinder will be assessed. These conclusions will be also used to improve Air Liquide technical procedures and recommendations for users and designers.

## 4 Conclusions

Through H2E program, Air Liquide develops $H_2$ safety knowledge in order to implement a specific safety strategy and accelerate the development of regulations and standards. This work will contribute to achieve public acceptance of hydrogen energy applications .

### References

[1] O Gentilhomme, I Tkatschenko, G Joncquet, F Anselmet, In: Proceeding of International Conference and Trade Fair on Hydrogen and Fuel Cell technologies, Hamburg, Germany (2008)

[2] JM Lacome, Y Dagba, D Jamois, L Perette, C Proust, In: Proceeding of ICHS2, San Sebastian, Spain (2007)

[3] S Gupta, J Brinster, E Studer, I Tkatschenko – In: Proceeding of ICHS2, San Sebastian, Spain (2007)

[4] B Cariteau, J Brinster, E Studer, I Tkatschenko, G Joncquet, In: Proceeding of ICHS3, Ajaccio, France, 2009

[5] Nathan Weyandt, NHTSA, DOT HS 811 150, 46 p. (June 2009)

[6] SA Matemilola, WJ Stronge, Journal of Pressure Vessel Technology, 119, 435-443 (1997)

[7] SR Swanson, NL Smith, Y Qian, Composite Structure, 18, 95-108 (1991)

# Selecting Hydrogen Embrittlement Resistant Materials by Means of the Disc Rupture Test

**Elke Leunis**, **Lode Duprez**, OCAS NV, ArcelorMittal Global R&D Gent, Belgium

## 1 Introduction

In industry, metals and alloys are often used in hydrogen rich environments. Hydrogen sometimes has a detrimental effect on the mechanical properties of metals, depending on the alloy, the microstructure, the environment, the stress state etc.

In many cases hydrogen related studies on laboratory scale are performed by introducing the hydrogen artificially into the metal via cathodic charging [1]. For applications with high pressure hydrogen gas it is however important to test the alloys in more realistic conditions.

The disc rupture test, a standardized test to select materials for hydrogen pressure vessels, is used to evaluate high strength materials in contact with gaseous hydrogen under pressure. In this test a circular specimen is loaded up to rupture. The rupture pressure ratio of helium to hydrogen is determined for different pressure increase rates, which results in the embrittlement index of the material. The disc rupture test was already discussed many years ago to evaluate the hydrogen effect on materials [2,3,4,5]. In many cases cathodically charged specimens were tested under He and compared with uncharged specimens. The disc rupture test is a fast and reliable tool to screen the hydrogen embrittlement behaviour of lab as well as industrial materials.

In this study, different metallic alloys are tested with the disc rupture test. The rupture appearance is studied to obtain a more profound understanding of the fracture mechanisms. Additionally, the materials are electrolyticaly charged to compare their behaviour. The comparison of the different methods will result in an evaluation of the use of the disc rupture test for selecting hydrogen embrittlement resisting materials.

## 2 Experimental

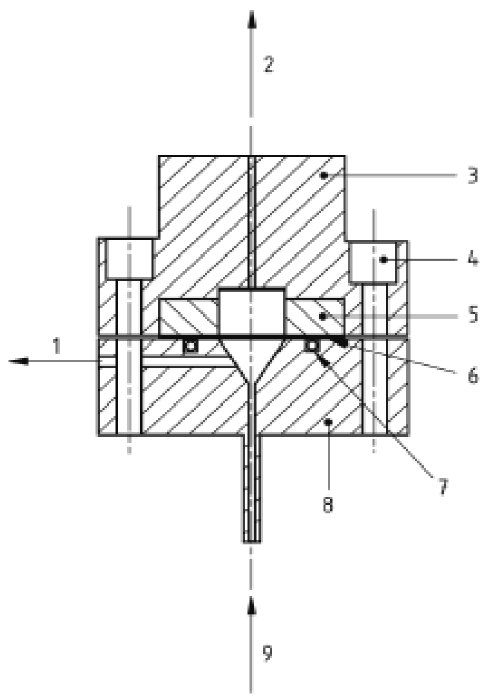
Materials. A selection of ferrous and non-ferrous alloys is used in this study: stainless steel, aluminium, nickel, titanium and copper based alloys. The mechanical properties are summarized in Table 1. Industrially produced materials are used. Diffusion coefficients from literature are given in Table 2.

**Table 1: Mechanical properties.**

| Grade | Material | Thickness | Rp0.2 | Rm | A50 |
|---|---|---|---|---|---|
| | | [mm] | [MPa] | [MPa] | [%] |
| SS 304 | austenitic stainless steel | 0.8 | 290 | 676 | 54 |
| SS 316 | austenitic stainless steel | 1.0 | 279 | 613 | 48 |
| SS 430 | ferritic stainless steel | 1.0 | 306 | 497 | 29 |
| Inconel 718 | Ni-alloy | 1.0 | 457 | 898 | 44 |
| OFHC Copper | Copper | 1.0 | 200 | 269 | 36 |
| A6061 | aluminum alloy | 1.6 | 272 | 336 | 19 |
| Ti-6Al-4V | titanium alloy | 1.0 | 1053 | 1063 | 10 |

**Table 2: Literature data on the diffusion of hydrogen.**

| | $D_0$ | $H_D$ | $D= D_0 \exp(-H_D/RT)$ | Ref |
|---|---|---|---|---|
| | $m^2.s^{-1}$ | $kJ.mol^{-1}$ | $m^2.s^{-1}$ | |
| **Austenitic SS** | $5.79 \times 10^{-7}$ | 53.62 | $2.3 \times 10^{-16}$ | [6] |
| **Ferritic SS** | | | $1.73 \times 10^{-12}$ | [7] |
| **Inconel 718** | $4.06 \times 10^{-7}$ | 48.63 | $1.2 \times 10^{-15}$ | [8] |
| **OFHC copper** | $1.06 \times 10^{-6}$ | 38.5 | $1.9 \times 10^{-13}$ | [9] |
| **Pure Aluminum** | $1.75 \times 10^{-8}$ | 16.2 | $2.5 \times 10^{-11}$ | [10] |




1. evacuation port/ flow adjustment
2. discharge port
3. upper flange
4. bolt hole
5. high strength steel ring
6. disc
7. O-ring
8. lower flange
9. gas inlet

**Figure 1: Lay-out of the disc pressure test.**

Disc rupture test. In the disc rupture test a mounted disc sample is subjected to increasing gas pressure at a constant pressure increase rate (Figure 1). The embrittling effect of hydrogen is evidenced by comparing the hydrogen rupture pressures $P_{H2}$ with the helium rupture pressures $P_{He}$, helium being chosen as a reference gas. The rupture pressure ratio $P_{He}/P_{H2}$ shall be determined. The lower this ratio, the better the material behaves in the presence of hydrogen. The discs with diameter 58 mm are punched from the original sheet. No additional surface preparation or thinning was performed, except for the A6061 alloy which was polished down to 0.75 mm.  Pressure increase rates between 1 bar/min and 100 bar/min are applied to compare the materials. The test temperature is 20°C in all cases.

The fractured surface for samples tested under helium and hydrogen are examined with the scanning electron microscope (SEM).

Cathodic charging. Samples of 10 x 6 mm were charged cathodically in a poly-carbonate cell between two symmetric Pt anodes. The electrolyte used in the tests is a sulfuric aqueous solution containing thiourea (1 g $CSN_2H_4$ + 0.5M $H_2SO_4$ / 1l $H_2O$). The samples were charged for 1h at room temperature using a varying current density up to 100 mA/cm² to evaluate the influence of the charging conditions. After charging, the samples were cleaned with distilled water and acetone, the surface and edges were polished to remove the electrolyte and cleaned again with distilled water and acetone. Immediatelly after charging, the hydrogen content was determined via melt extraction with a Bruker G8 Galileo equipment.

## 3 Results & Discussion

Disc rupture test. The rupture pressure ratios for the ferrous and non-ferrous alloys as a function of the pressure rise rate are given in Figure 2.  A pressure ratio of 1 means no effect of the hydrogen, while all higher values indicate a HE effect.

The test results reveal that the high pressure hydrogen atmosphere does not have any embrittling effect on the austenitic 316L SS, while it is significantly affecting the properties of the 304 SS. For the 430 SS grade the hydrogen only has an effect for low pressure rise rates, i.e. low deformation rates.

In general austenitic stainless steels are less susceptible to HE due to the low hydrogen diffusivity (see Table 2) and the high hydrogen solubility. In the 316L SS the austenite is stable, even after deformation. In the 304 SS however the austenite is metastable and transforms to strain-induced $\alpha$'-martensite during deformation. This martensite enhances hydrogen uptake since hydrogen diffuses more rapidly in BCC phases and make the material more vulnerable to HE.

In the ferritic 430 SS the embrittlement is dependent on the strain rate which is determined by the pressure rise rate. The local strains enhance the local uptake of hydrogen and micro-cracks are formed.  For slow strain rates, the exposure time to the hydrogen gas is higher and also the hydrogen has more time to diffuse and to recombine in the deformed matrix.

Most of the tested non-ferrous alloys seem to be insensitive to HE under high pressures.  In the Inconel 718 alloy the HE effect increases significantly with lower deformation rates, which can be explained by the same mechanism as for the 430 SS discussed above. It is known from literature that the Inconel 718 alloy is sensitive to HE [8,11]. This embrittlement is related to the presence of strengthening phases $\gamma$' and $\gamma$'' and the grain boundary phase $\delta$.

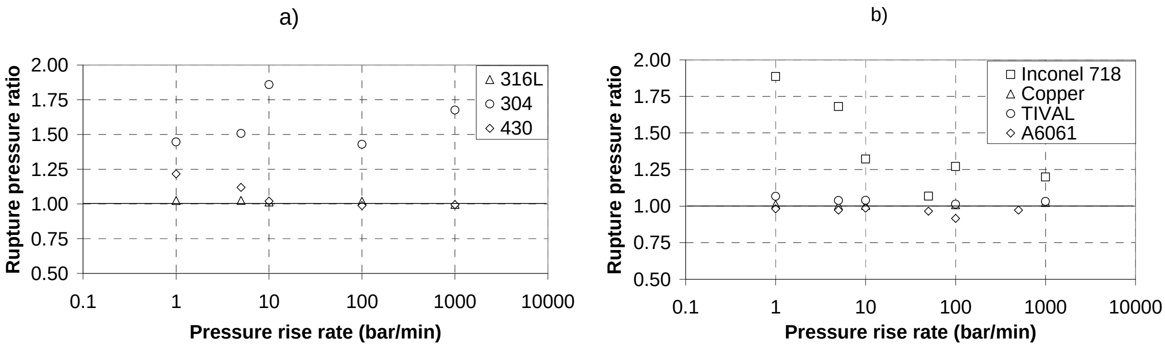



**Figure 2: Rupture pressure ratio as a function of the pressure rise rate a) ferrous alloys b) non-ferrous alloys.**

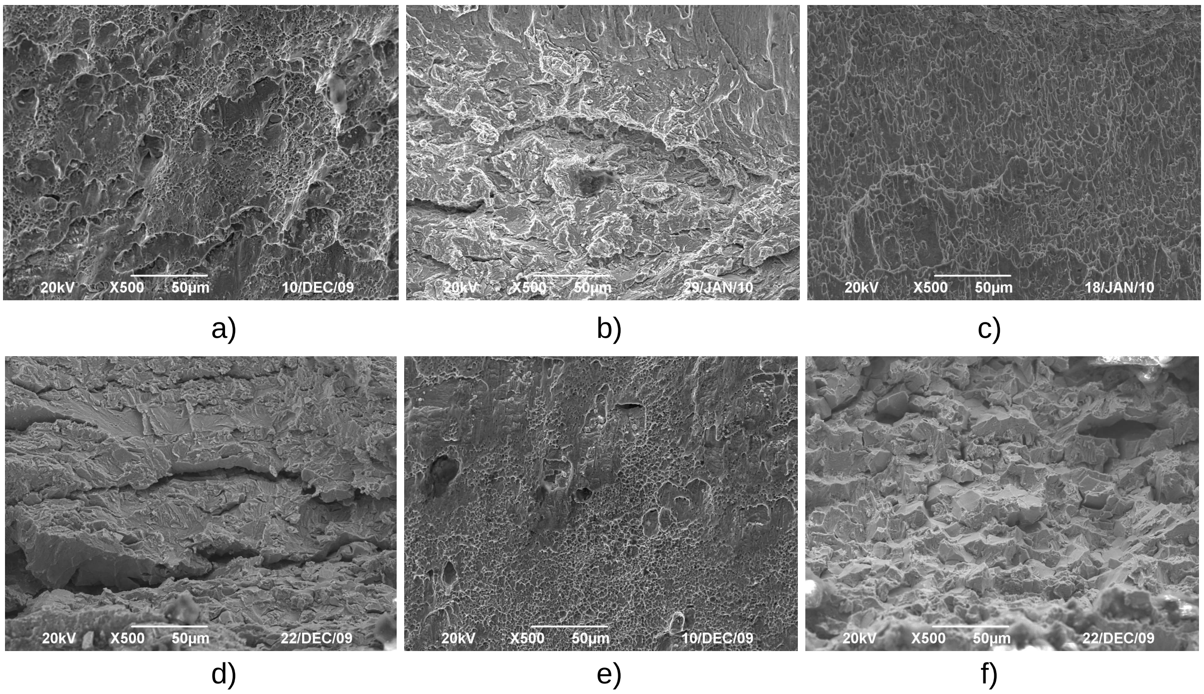



**Figure 3: Fracture surface after disc rupture test: a) Inconel 718 at 1 bar/min in He; b) SS304 at 1 bar/min in $H_2$; c) SS430 at 1000 bar/min in $H_2$; d) SS430 at 1 bar/min in $H_2$; e) Inconel 718 at 1000 bar/min in $H_2$; f) Inconel 718 at 5 bar/min in $H_2$.**

<u>Fracture analysis.</u> Results from the scanning electron microscope observations on fracture surface after disc rupture testing are presented in Figure 3. All specimens exhibited ductile fracture after helium testing for which an example of Inconel 718 is given in Figure 3.a.The samples that not revealed any HE effect, such as the 316L SS, copper, Ti-6Al-4V and A6061, had a similar ductile fracture after testing in hydrogen.

For 304 SS the fracture surface in hydrogen was brittle and transgranular for all testing conditions. For the alloys 430 SS and Inconel 718, the hydrogen sensitivity is strain rate dependent. Ductile fractures are observed for high pressure rise rates and brittle fractures for low pressure rise rates. In the SS430 a brittle cleavage fracture occured, while the fracture in Inconel 718 is clearly intergranular.

Cathodic charging. During cathodic charging, the samples were saturated with hydrogen. After charging, hydrogen is assumed to be present in both interstitial lattice places as well as near lattice defects, *i.e.* at hydrogen traps. Figure 4 gives an overview of the hydrogen content of the samples charged for 1h with different current densities.

It is clear from Figure 4 that for identical charging conditions, the hydrogen content in the materials is different. This is related to the difference in solubility of hydrogen in the crystal lattices, the hydrogen diffusion coefficients and the surface status of the alloys. Diffusion coefficients from literature are given in Table 2.

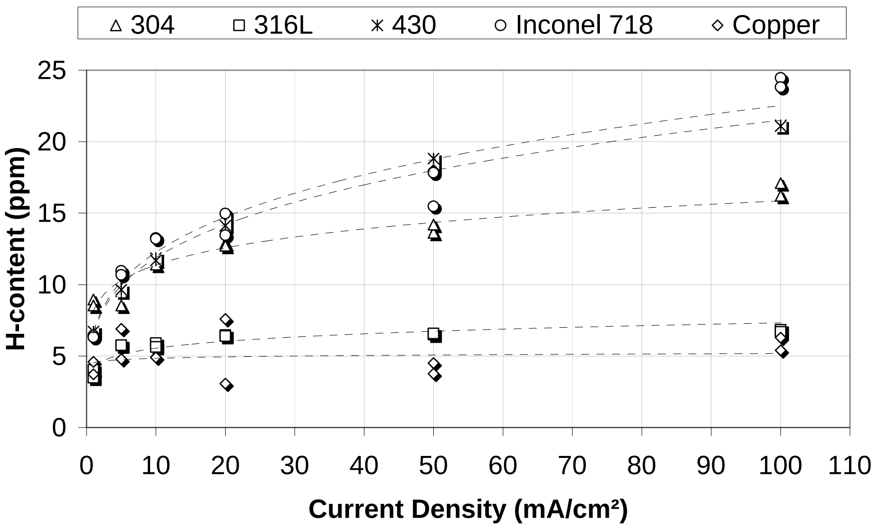



**Figure 4: Overview of the hydrogen content of the samples charged for 1h with different current densities.**

In the disc rupture test, the hydrogen uptake takes place from the high pressure gaseous phase. In the cathodic charging, the hydrogen is electrochemically forced to enter the material which makes the testing conditions more severe. However the same tendencies as for the disc rupture test are noticed with cathodic charging. Almost no hydrogen is taken up in the 316L SS and copper material. They didn't show any embrittlement during disc rupture testing neither. In the ferritic 430 SS and the Inconel 718 alloys, the hydrogen charging is high. For the austenitic 304 SS in the non-deformed state however, the same behaviour is expected as for the 316 SS, because of the very low hydrogen diffusivity in austenite. However, the samples are much more charged than the 316 SS. This makes us assume that surface effects are playing. This needs further investigations.

## 4 Conclusions

Disc rupture tests were performed on different ferrous and non-ferrous alloys in helium and hydrogen atmosphere. The ratio of the rupture pressures in both gases gives an idea of the HE and allows to select HE resistant materials for gaseous applications.

The stable austenitic 316 SS does not show any HE with the disc rupture test. The metastable 304 SS embrittles after gaseous hydrogen exposure combined with deformation because strain induced martensite forms. The HE of the ferritic 430 grade is dependent on the strain rate.

The tested copper, aluminium and titanium alloys did not show any HE during disc rupture testing. The Inconel 718 does show strain rate dependent HE. The obtained results are in agreement with literature.

The disc rupture test results were in agreement with results obtained after cathodic charging.

**References**

[1] Mertens G., Duprez L., De Cooman B.C., Verhaege M., Advanced Materials Research, Vols.15-17 (2007), pp. 816-821

[2] Fidelle, J. P., Broudeur, R., Pirrovani, C., and Roux, C., ASTMSTP543, 1974, pp. 34-47.

[3] Fidelle, J. P., Bernardi, R., Broudeur, R., Roux, C., and Rapin, M., ASTM STP 543, pp. 221-253.

[4] Fidelle, J.-P., ASTM STP 962, 1988, pp. t53-172.

[5] Beghini M. ; Benamati G. ; J. Eng Mat Technol (1996) Vol. 118, 179-185

[6] XK Sun, J Xu and YY Li. Mater Sci Eng A114 (1989) 179-187

[7] S.K. Yen, I.B. Huang / Materials Chemistry and Physics 80 (2003) 662–666

[8] L. Fournier, D. Delofosse, T. Magnin, Mater Sci Eng A269 (1999) 111-119

[9] WG Perkins. J vac Sci Technol 10 (1973) 543-556

[10] GA Young and JR Scully, Acta Mater 46 (1998) 6337-6349

[11] L.Liu, K. Tanaka, A. Hirose, K.F. Kobayashi, Sci Technol Adv Mat 3 (2002) 335-344

# GASTEF: The JRC-IE Compressed Hydrogen Gas Tanks Testing Facility

**B. Acosta**, **P. Moretto**, **N. Frischauf**, **F. Harskamp**, Joint Research Centre of the European Commission, Institute for Energy

## 1 Introduction

Hydrogen can be stored in many ways as metal hydride tanks, compressed gas, cryo-liquified, carbon nanotubes, gas micro spheres, liquid carrier or chemical storage. However, for on-board applications, both compressed gas and liquid hydrogen have established themselves as state of the art.

The storage of gases under pressure, including hydrogen, is a well-known technology. Nonetheless, the use of hydrogen tanks in vehicles and in particular the challenge of using very high pressures, demands stringent regulations supported by safety and performance studies. Requirements to qualify storage systems for on-road passenger vehicles have been under development primarily by the SAE International and ISO committees (respectively SAE-J2579 [1] and ISO15869 [2]). The push to develop safety standards for hydrogen storage well before commercialization is driven by two factors. First, acknowledging that on-road safety is of highest priority, requirements are being developed a-priori, without waiting for any lessons learned from on-road experience. Second, taking into account that there is a high need for rapid insertion of new technologies into the marketplace, storage requirements must be capable of qualifying novel technologies for reliable and durable performance under broad conditions of use. Setting up qualification test campaigns with conditions that take into account historical failure mechanisms is helpful but not sufficient. Instead a comprehensive approach to defining extreme conditions of on-road vehicle service is required. Storage systems must function both under the stresses of normal vehicle operation and under externally imposed stresses.

Today's state of the art for hydrogen storage comprises 35 MPa (350 bar) and 70 MPa (700 bar) compressed gas tanks. Carbon fiber fully wrapped-reinforced tanks are already in use in prototype hydrogen-powered vehicles. Two types of inner liners are typically used: metal (aluminium, Cr-alloys) ones in "Type 3" storage pressure vessels and high molecular weight polymer in "Type 4" tanks, as described in ISO 15869 [2]. The application of such materials comes from the need of guaranteeing impermeability of the inner liner to the hydrogen molecules whilst having the tank being as lightweight as possible.

Both SAE 2579 and draft ISO 15869 propose the following tests for compressed hydrogen storage tanks:

- Sequential exposure to impact, chemicals and cyclic stresses
- Sequential exposures to static high pressures (simulates vehicle parking) and fuelling stresses
- Exposure to hydrogen fuelling under extreme ambient temperatures
- Simulated fuelling failure (i.e. overpressures) at the end of vehicle service

To carry out “expected-service performance verification tests” on full-scale high pressure vehicle’s tanks for hydrogen or natural gas, the JRC-IE has set up a facility, dubbed GasTeF (for Gas Testing Facility). In addition the testing of any other high-pressure components, such as valves and pipes, is also possible.

## 2 Facility Description

The JRC-IE compressed hydrogen gas tanks testing facility consists of a half-buried concrete bunker with an attached gas storage area. The bunker is analogous to bunkers designed for the storage of explosives such as dynamite; it has double walls of heavy-concrete and is covered by a three meter thick sand layer armored by geotextile every thirty centimeters so that it could endure a sudden energy release equivalent to 50 kg TNT [3]. In this way the impact of a potential hydrogen explosion in the vicinity of a nuclear installation is fully mitigated.

The bunker is divided into three parts: a service room, the compressor room and the test room, see Figure 1. All the relevant equipment inside the bunker is explosion proof zone 2 according to the ATEX 137 EC directive [4].

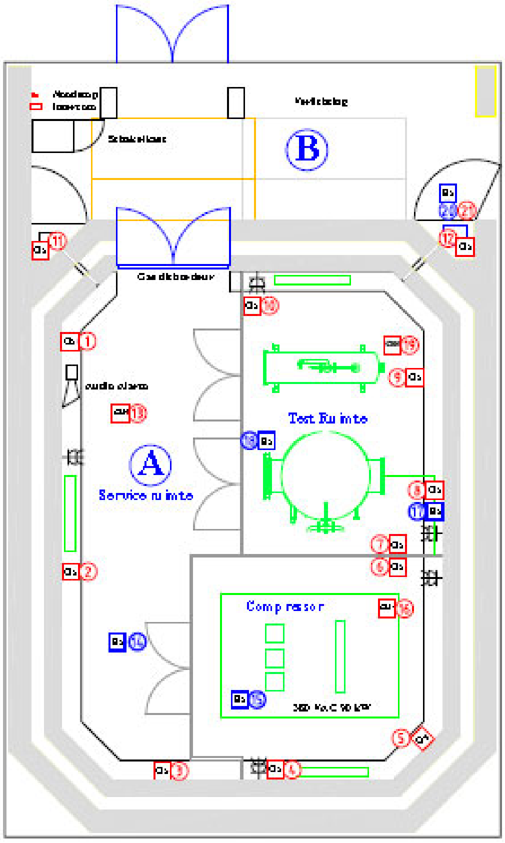



**Figure 1: Overview of the inside of the GasTeF rooms and surveillance/safety devices.**

The compressor room houses a two stages compressor enabling hydrogen or methane to pressurize and depressurize the test tank (i.e. fuelling and defuelling), Figure 2. The compressor is a piston machine built by Hofer and is able to fill a gas tank to a pressure of 88

MPa with a power consumption of 55 KW within 3 minutes. It is cooled using a closed water circuit that includes an air/water heat exchanger located outside the bunker. The compressor is equipped with its own PLC (Programmable Logic Controller) for full remote control. The PLC collects all signals from the machine and the cooler and performs its own continuous functional checks. Part of the information collected by the compressor PLC is transferred to the main control and automation PLC of the facility via a bi-directional link.

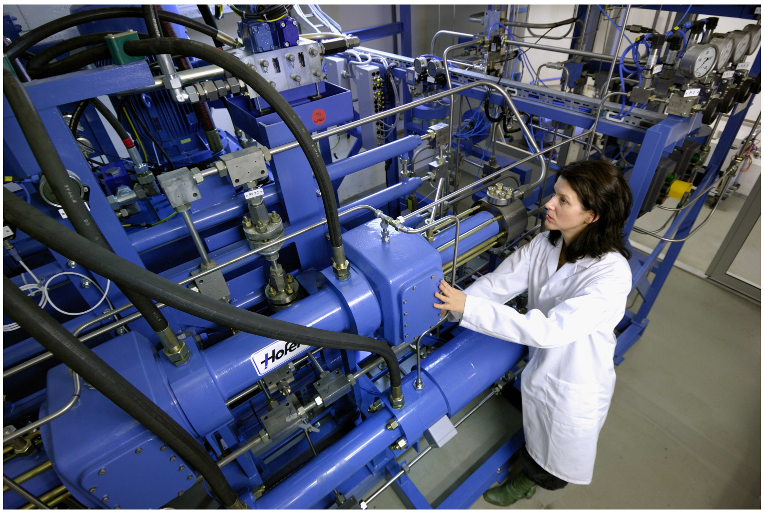


**Figure 2: GasTeF compressor.**

**Figure 3: Safety pressure vessel.**

In the test room a pressure vessel containing the component to be tested is placed, see Figure 3. The fuel tanks are inserted inside a sleeve which contains an inert gas (helium or nitrogen) and serves as a chamber for determining hydrogen permeation through the test tank walls. The hydrogen level in the sleeve is accurately determined using a gas chromatograph. The sleeve is placed into the safety pressure vessel which is filled with nitrogen at 5 kPa, so that hydrogen leakages will stay safely contained within a small volume. In the case of hydrogen/methane leakages outside the pressure vessel, into the test room, the emergency shut down procedure will automatically start.

The compressor and the test installations are linked with high pressure stainless steel piping. Besides control valves and pressure and temperature indicators, the system is equipped with safety valves and pressure reducers for emergency venting. The facility features also stacks for the controlled or urgent discharge of gases in the air.

The bunker is closed by a gas-tight inner door and after that by a hydraulically operated 40 tons massive concrete door sliding on Teflon plates. During tests, the bunker is deprived of oxygen by purging with nitrogen gas in order to prevent the occurrence of an explosive atmosphere created in the event of leakages. In normal operation the facility will be run fully automatically and the tests are operator controlled from a control room situated in an adjacent building.

Inside the bunker a number of gas detectors are strategically situated as Figure 1 shows. There are three types of sensors: Oxygen, hydrogen and methane content detectors, whereby all are placed inside each room in the bunker. The gas detectors form the heart of the safety monitoring system of the bunker, so special attention has been paid to their working logic:

In each room there are three oxygen sensors from which the signal of at least two must be valid in order to carry out the testing (the red squares in Figure 1). When the bunker is closed and filled with nitrogen, the oxygen content must be kept to a value less than 0.9%. On the contrary when the test is finished, the oxygen sensors have to measure more than 19%, before the bunker is allowed to be opened.

$H_2$ and $CH_4$ Sensors: There is a hydrogen and a methane detector in atmosphere inside each room and in the left niche of the bunker where the gas chromatograph is located (blue squares in Figure 1). In addition there are other $H_2$ and $CH_4$ sensors in the line going out from the sleeve to the gas chromatograph and to the exhaust stack. If one of the detectors measures a hydrogen content exceeding 80% of LEL the emergency shut down procedure is immediately triggered.

The emergency shut down procedure ensures that the three bunker rooms and all installation parts (piping, etc.) are purged with nitrogen gas. When all the hydrogen/methane has been vented-off, the ventilation system will fill all bunker rooms with air to regain a breathable atmosphere after which the concrete door can be opened and the bunker accessed.

## 3 Tank Performance Testing

GasTeF is designed to carry out the following experiments in both Type 3 and Type 4 cylinders:

Fast-filling cycling, in which storage tanks are fast filled and slowly emptied using hydrogen pressurized up to 70 MPa, for at least 1000 times to simulate their lifetime in a road vehicle. During the cycling process the tank is monitored for leaks and permeation rates using gas chromatography.

Static permeation measurements as a function of time on tanks filled up to 70 MPa and temperatures to 85 °C.

Figure 4 shows an example of fast filling experiment performed in GasTeF. In this case the target filling pressure was 350 bar and it took 2.5 minutes to fill in a 30 liters Type 4 tank. The emptying time was about 40 minutes. Figure 4 showcases how the tank temperature increases during the first filling cycles to reach a stable value of approx. +23 C° after six filling/emptying cycles.

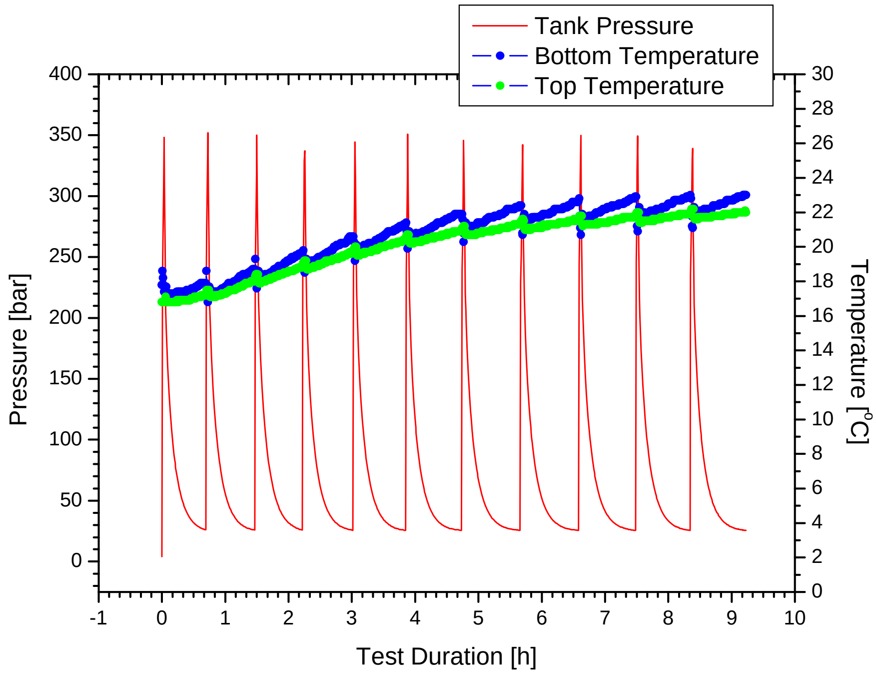



**Figure 4: Example of a fast filling test.**

A first example of a “permeation type” test carried out after the cycling depicted in Figure 4 can be seen in Figure 5. Here the tank pressure decreases sharply within the first 30 minutes and reaches an equilibrium pressure of 300 bar after 1.5 hours. The pressure drop seems to be primarily caused by the temperature decrease of the tank.

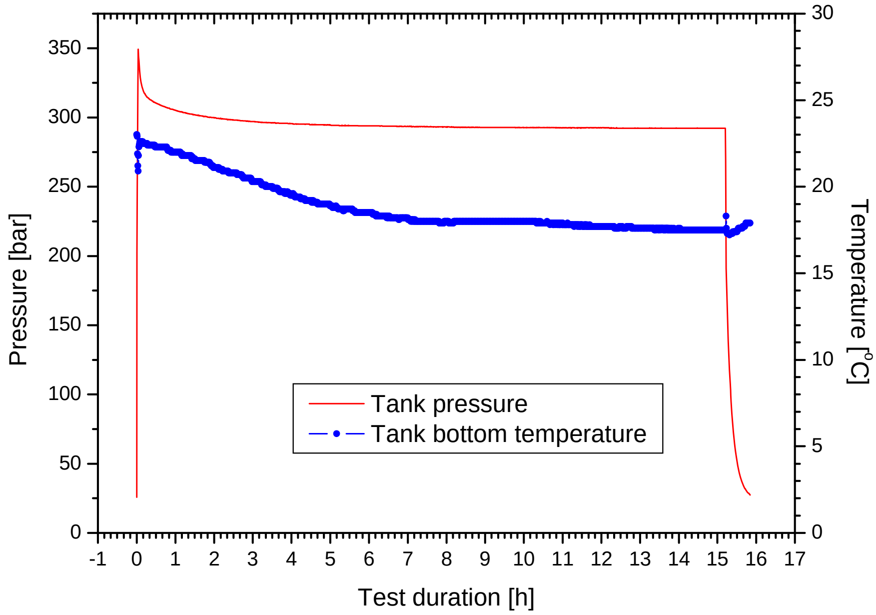



**Figure 5: Example of a permeation test.**

This activity is part of a more general effort aiming at assessing from a safety point of view existing and future regulation in the field, and in particular the measures drafted in the implementing European regulation on type-approval of hydrogen vehicle [5]. The GasTeF results will be applied to validate existing and future standards and will be used as input to pre-normative research for the development and improvement of performance characterization methodologies for hydrogen storage.

**References**

[1] SAE J2579 Technical Information Report for Fuel Systems in Fuel Cell and other Hydrogen Vehicles, SAE International, Issue 2008

[2] ISO/CD 15869-Gaseous hydrogen and hydrogen blends – Land vehicle fuel tanks, ISO 2001

[3] “Design of the hydrogen test facility of the Joint Research Centre in Petten, Netherlands” Ing. A.H. Verhagen, KEMA, Breda, June, 2003

[4] ATEX 137 Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres, European Directive 1999/92/EC, Official Journal of the European Communities L23/57, 28 January 2000

[5] Draft EC regulation, implementing Regulation (EC) No 79/2009 of European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles, Brussels July 2009.

# Performance Testing of a MOSFET Sensor

**Grainne Black, Lois Brett, Pietro Moretto**, European Commission JRC-IE
**Jaroslav Bousek**, Brno University of Technology, Czech Republic

## 1 Introduction

The widespread use of hydrogen as a fuel will bring new challenges in terms of safety and hydrogen safety sensors will therefore play an important role in such a hydrogen economy. Devices for the detection and quantification of hydrogen are well-established in controlled industrial and laboratory environments. In the future however, hydrogen safety sensors will be used more widely and under a greater range of ambient conditions for the protection of people and property. In this context, independent performance testing of such sensors is extremely important to ensure that they can accurately and reliably alert to the presence of hydrogen under the expected conditions of operation.

The sensor testing facility of the JRC-IE has been developed for this purpose and has previously been used in an extensive testing campaign involving a range of hydrogen sensing technologies [1]. Presented here are the results of tests on 2 identical commercially available MOSFET (Metal Oxide Semiconductor Field-Effect Transistor) sensors. These devices are field-effect transistors based on a triple layer structure consisting of a catalytic gate metal, an insulator (oxide) and a semiconductor layer. Adsorbed hydrogen molecules on the metal surface dissociate and diffuse to the metal-oxide interface where they produce a change in the electrical properties of the transistor, which can be correlated to the hydrogen concentration in the ambient atmosphere [2].

The performance of these sensors has been tested in terms of their accuracy, measuring range, cross-sensitivity to CO, as well as the influence of ambient temperature, pressure and relative humidity on their response. These results are compared with those obtained previously for a number of other sensor types.

## 2 Experimental and Results

The sensor testing facility (SenTeF) at the Institute for Energy of the JRC will be described briefly here, but a more detailed description is available in the literature [3,4,5]. It consists of a 2.4L test chamber in which sensors are mounted, a gas handling system, a control and data acquisition system and an independent gas analyzer, as well as subsidiary devices for temperature management and power supply. All electrical signals, including sensor input and output are transmitted to and from the chamber via two 25-pin feedthroughs. Gas is introduced into the bottom of the chamber and leaves from the top, while a fan is positioned inside the chamber to ensure homogeneity of gas composition and temperature. Gases are mixed online and humidified using a Bronkhorst® controlled evaporator mixer. Test gas humidity is measured using a chilled mirror dew point meter. The temperature in the chamber is controlled by circulating thermostatic fluid between the walls and is measured using three Pt100 thermometers. The actual composition of the gas in the chamber is monitored continuously using a compact gas chromatograph (GC) calibrated to quantify hydrogen concentration.

A series of tests was carried out to assess the performance of these sensors:

1. Accuracy of response
2. Measuring range
3. Detection limit
4. Cross sensitivity to carbon monoxide (CO)
5. Ambient temperature
6. Ambient pressure
7. Ambient relative humidity

The procedure for carrying out these performance tests was developed based on that described in IEC 61779 and will be outlined briefly here, although more detail is available in the literature [3]. The standard test conditions for all tests were:

Temperature: 298 ± 2 K

Pressure: 100 ± 2 kPa

Relative humidity: 50% RH (dew point 13.8 ± 1.8 ºC)

Gas flow rate: 1000 ± 20 nml/min

In the ambient parameter tests, only the relevant parameter was varied and otherwise the conditions remained as above.

## 2.1 Sensors

The MOSFET sensors under test are commercially available devices, designed for installation in vehicles and hydrogen fueling stations. Relevant specifications given by the manufacturer are as follows:

**Table 1: Technical specifications of MOSFET sensor.**

| | |
|---|---|
| **Accuracy** | ± 3000 ppm |
| **Measuring range** | 0 – 4.4% H2 in air |
| **Operating temperature** | -40 – 110ºC |
| **Pressure** | 70 – 130 kPa |
| **Humidity** | 5 – 95% |
| **Cross sensitivity towards CO** | None |
| **Influence of humidity** | None |

## 2.2 Accuracy

Sensors were exposed to a gas mixture whose concentration was increased in a stepwise fashion from 0.0 to 2.0 vol% and then decreased in the same way. Control of the gas concentration was achieved by online mixing of 2 vol% hydrogen in air with synthetic air and the maximum concentration tested was 2 vol% for safety reasons. At each concentration, the sensor response and GC reading were allowed to stabilize before proceeding with the subsequent step. This test was performed immediately before the measuring range test described below.

Results are shown in the left part of Figure 1. The two sensors gave almost identical responses. They are highly accurate, deviating by a maximum of 2020 ppm from the GC values over the range of hydrogen concentration investigated. Although the deviation of the sensor response in ppm increases steadily with increasing hydrogen concentration, this deviation as a % of the GC value decreases as the hydrogen concentration increases. Relative to the actual hydrogen concentration therefore, the accuracy of these sensors increases as the hydrogen concentration is increased within the range 0 – 2 vol%.

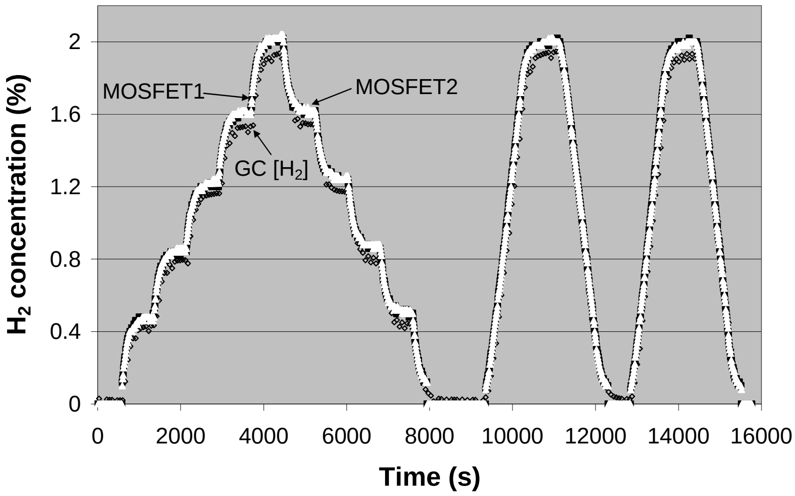



**Figure 1: Results of accuracy and measuring range test.**

## 2.3 Measuring range

The purpose of this test was to monitor the response of sensors to changing hydrogen concentration. The sensors were exposed to a test gas mixture which was increased steadily in concentration from 0.0 to 2.0 vol% $H_2$ and then decreased again. The process was repeated immediately in order to reveal any evidence of hysteresis or memory effects.

The results of the measuring range test are shown in the right hand part of Figure 1. In both cases, the sensor response increases and decreases in line with that of the GC and with no evidence of hysteresis.

## 2.4 Detection limit

The aim of this test was to determine the lowest concentration of hydrogen that these sensors were capable of detecting. The hydrogen concentration in the test gas was increased incrementally from 0.0 vol% until a definite increase in sensor output, distinct from baseline noise, was observed. However, the lowest concentration of hydrogen that could be accurately mixed during this test was 0.03 vol% and both sensors were found to give a well-defined response at this concentration. Therefore the detection limit could not be determined exactly, but must lie below 0.03 vol% $H_2$ in air.

### 2.5 Cross sensitivity to CO

The test gas consisted of a constant flow of 2.0 vol% $H_2$ in air and a mixture of synthetic air and 0.51 vol% CO in nitrogen. The relative flows of synthetic air and $CO/N_2$ were varied stepwise in order to control the concentration of CO in the test gas mixture. The CO concentration was varied until a deviation in the sensor signal equivalent to 0.4 vol% $H_2$ (10% LFL) was observed. The sensor cross sensitivity to CO is expressed here as the concentration of CO required to produce this signal deviation.

The response of these sensors to different concentrations of CO in a 1 vol% hydrogen/air mixture is shown in Figure 2. It can be seen that an increase in the CO concentration leads to a proportional decrease in the sensor signal. The deviation in both sensor signals from their readings in the absence of CO was –0.32% at the maximum CO concentration tested of 2540 ppm. Extrapolation of the data gives a signal deviation of 0.4 vol% at a CO concentration of 3150 ppm.

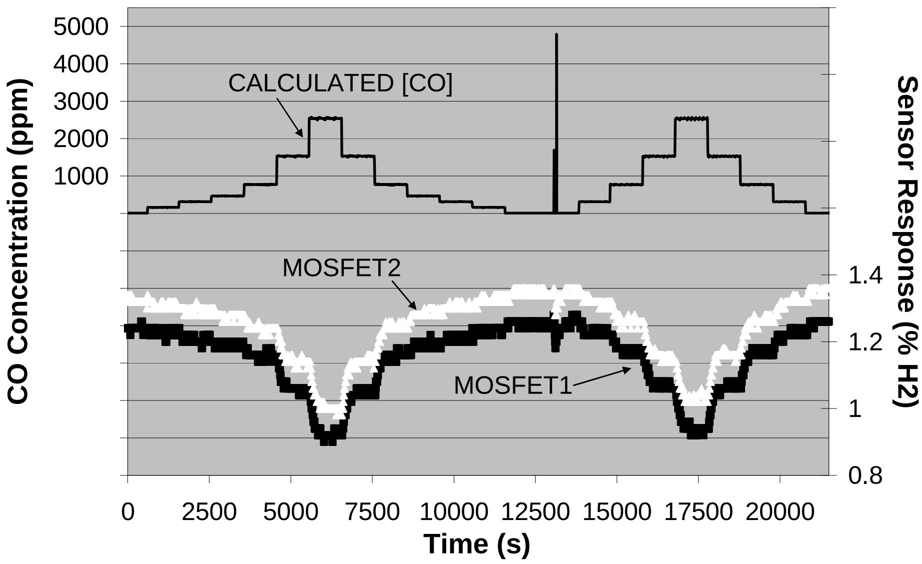



**Figure 2: Results of CO cross-sensitivity test.**

### 2.6 Ambient temperature

The purpose of this test was to examine the influence of temperature on the sensor signal in both the absence and presence of hydrogen. At each of five temperatures (-15, 5, 30, 60, 80ºC) within their operating range the sensors were exposed first to clean air and then to 2 vol% $H_2$ in air. There is no apparent influence of temperature on sensor response within the range -15 to 80ºC. Results of this test are shown in Figure 3.

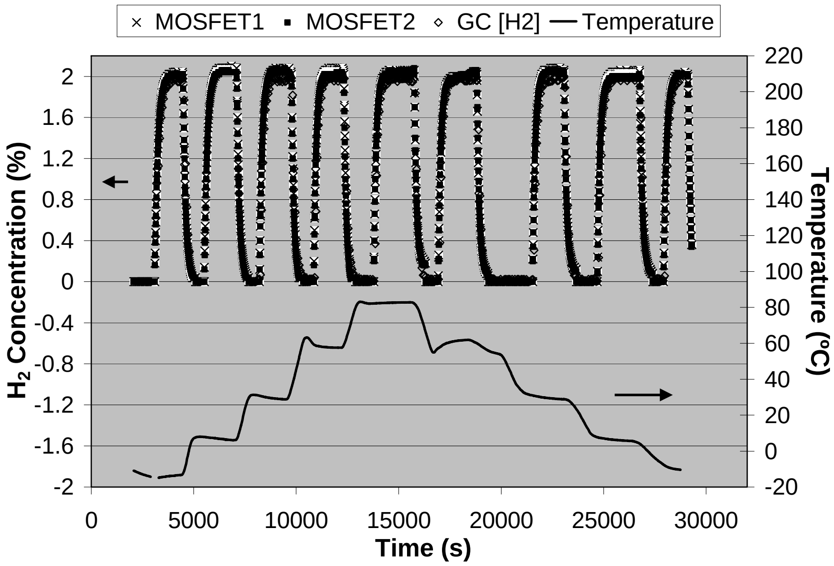



**Figure 3: Results of temperature test.**

## 2.7 Ambient pressure

Similar to the ambient temperature test method, the sensors were exposed to clean air followed by 2 vol% $H_2$ in air at a number of pressures (80, 90, 100, 120 kPa) within their operating pressure range as a means of determining the influence of ambient pressure on sensor response. As with temperature, there was found to be no detectable influence of pressure within the range tested.

## 2.8 Ambient humidity

In order to assess the influence of ambient humidity on sensor response, the sensors were exposed to clean air and then 2 vol% $H_2$ in air at a number of relative humidities (20, 40, 60, 80%) distributed over the operating range specified by the manufacturer. The sensor signal was found to be independent of humidity at both 0 and 2 vol% $H_2$ over the dew point range tested.

## 2.9 Comparison with other sensor types

An identical series of tests was previously carried out on a number of other sensor types[1]. In Figure 4 the performance of the MOSFET sensors tested in this work is qualitatively compared with that of the catalytic, electrochemical, metal oxide semiconductor and thermal conductivity sensors previously tested. For each test each sensor type was assigned a number between 0 and 4 to represent its relative performance. The MOSFET sensors tested here were found to perform as well or better than the other sensor types in all tests except for cross-sensitivity to CO.

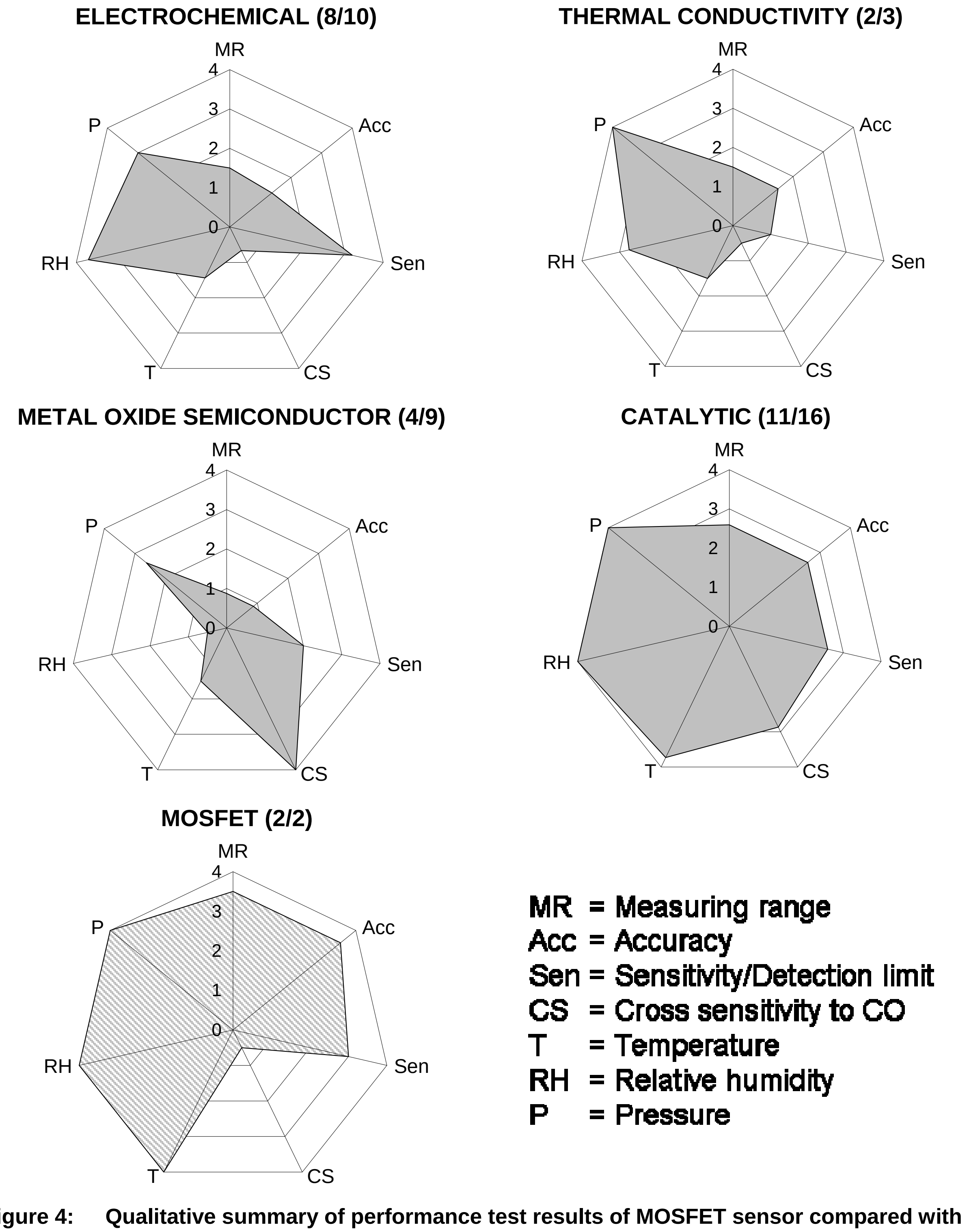



**Figure 4:** **Qualitative summary of performance test results of MOSFET sensor compared with other sensor types. Numbers in brackets represent the ratio of the number of functioning sensors to the number of sensors purchased.**

## References

[1] Boon-Brett L, Bousek J, Moretto P. Int J Hydrogen Energy 34 (2009) 562-571.

[2] Lundstrom I, Sensors and Actuators 1 (1981) 403-426.

[3] Boon-Brett L, Bousek J, Castello P, Salyk O, Harskamp F, Aldea L, Tinaut F. Int J Hydrogen Energy 33 (2008) 7648-7657.

[4] Castello P, Salyk O, Int Sci J Alternative Energy Ecology 5 (2006) 61-62.

[5] Salyk O, Castello P, Harskamp F. Meas Sci Technol 17 (2006) 3033-3041.

# Smart Fibre Optic Methods for Structural Health Monitoring of High Pressure Vessels for Hydrogen Storage

**Paweł Gąsior**, **Wojciech Błażejewski**, **Jerzy Kaleta**, Wrocław University of Technology, Poland

## 1 Introduction

High pressure composite tanks of IV generation (700 bar) for Hydrogen storage must fulfil sharp norm within safety. Simultaneously tank must be cheap and light. Conceptions „on board monitoring" making use of light fibres sensors appear especially promising. These sensors are inbuilt in the structure of composite without changing composite mechanical properties. Moreover, sensors are spark less and resistant against electromagnetic disturbance. They have large range of measurements and can easily collaborate with electric system of cars. The method is included in NDT.

Optimal solution requires hybrid approach what means the both numerical model of composite tank and measurement system are required. The numerical model allows an optimal arrangement of sensors reducing their number and current comparison of measured strains with values derived from model. The paper presents applications of two optical fibre based systems which create a structural health monitoring systems for high pressure vessels "on-line" monitoring. The original FEM model required application of so-called homogenisation procedures and it enabled determination of strains within variety of length scales as well as damage accumulation. Some results were obtained under StorHy project (6FP, Integrated Project).

## 2 Optical Fiber Sensors Built in the Composite Structure

Application of monitoring systems (periodical or continuous) to check up the effort state of composite vessels is becoming necessity because of safety requirements that must be met by gaseous fuel tanks (methane, hydrogen) in cars. Standard methods of visual inspection will not detect defects which may have critical influence on the technical status of the monitored construction, whereas typical measurement systems (e.g. resistance strain gauges) all too often get damaged in adverse environmental conditions [1,2,3]. Ever growing popularity in the field of monitoring technical condition of industrial objects is being gained (on-board monitoring system) by modern measuring methods based on optical fiber technology. It stems, among other things, from many advantages that optical fiber sensors have over standard methods. The obvious one being their application at high levels of electromagnetic interference and in other adverse conditions (high dust concentration, high temperature, high pressure, significant deformations). Moreover these sensors are characterized by high measuring sensitivity in wide ranges of measurements (deformation, temperature). Simultaneously due to their small geometric dimensions and relatively small mass, it is possible to position the measuring head inside the structure of the object (e.g. building them in into the composite material) or installation on its surface. Thanks to their high potential for multiplexation it is possible to create, the nervous system of the object being monitored. Additionally such applications like fuel tanks (with high degree of safety) regard to the so-called spark-proof safety [4].

In order strain state monitoring two types of optical fiber sensors were installed: point sensors in the form of FBGs as well as interferometric sensors with long measuring arms (SOFO®) [5]. A fiber Bragg Grating is a structure made in the core of a single-mode optical fiber (figure 1a), characterized by periodical changes in the value of the refractive index [6]. Presence of such a modulated structure inside the core of the optical fiber causes part of the optical radiation transmitted through the optical fiber to be reflected from the grating structure, and the remainder is propagated without any loss. The wavelength reflected from the Bragg grating, the so-called Bragg wave ($\lambda_B$) is described with the relation $\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$ ($n_{eff}$ – effective refractive index of the optical fiber core, $\Lambda$ – Bragg grating constant) [6].

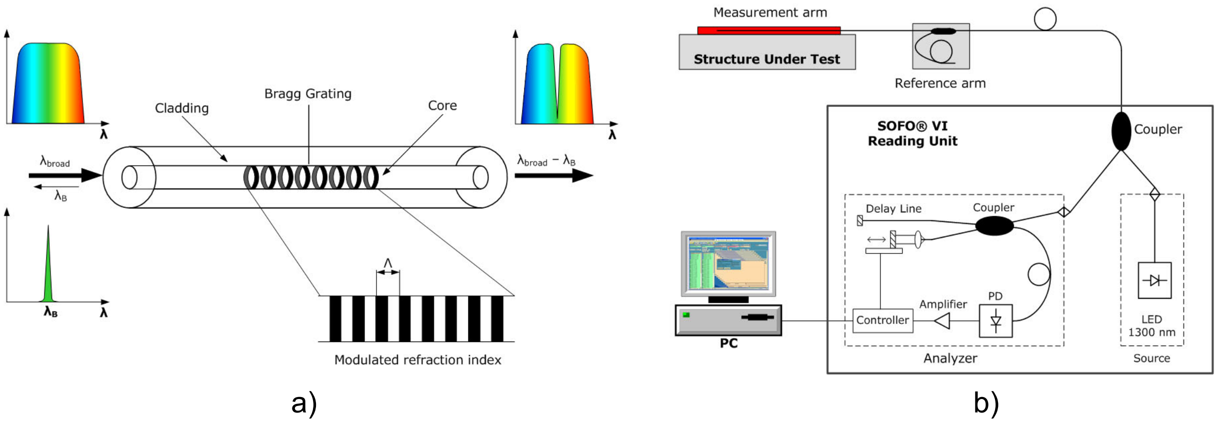


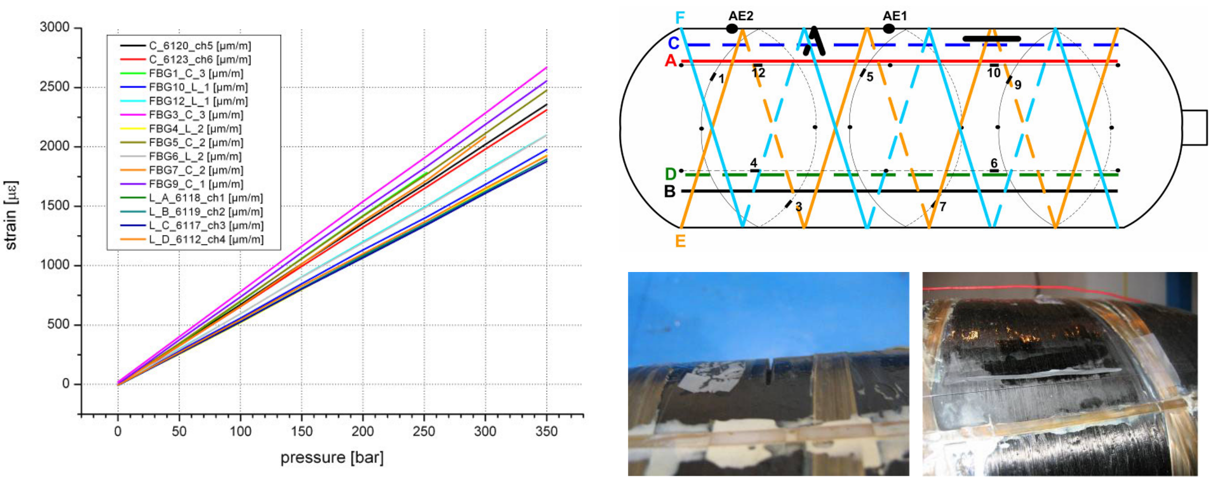

**Figure 1: Scheme of fiber Bragg gratings principle of operation (a) and scheme of Smartec SOFO interferometric measuring system (b) [on the basis of: 6,7,8].**

Sensors bonded to the external surface of the monitored construction, or located in the material structure are subjected to deformations causing change in Bragg wavelength, which becomes the touchstone for measured deformations. It should be emphasized, however, that change $\lambda_B$ in real measuring systems is the result of the simultaneous influence of temperature and deformations [6], which can be measured in ranges reaching: -270°C ÷ 800°C and -3% ÷ 3% respectively.

Interferometric optical fiber sensors (SOFO®) are characterized by modulation of light signal phase propagated in the measuring system. Measuring heads in the form of single-mode optical fiber may attain from a few centimeters to a dozen or so meters and are either integrated with the surface of the monitored object (e.g. in the shape of special tape – the so-called SMARTape) or located inside the monitored structure (and as in the case of test vessels are buried in the composite). These sensors are designed to measure displacements (deformations). The idea of measurement consists in analyzing the difference in phases of optical signals propagating in two arms of the Michelson interferometer – measuring and reference arms (figure 1b). The measuring arm is in direct contact with the examined construction. The reference arm is separated mechanically from the monitored object, but is nevertheless close enough for the temperature of both arms to be the same. This allows eliminating the influence of temperature fluctuation on measurement results. The change in the phase of the light wave which occurs is the result of the change in the length of the optical fiber constituting the measuring head. As a result of interference of both beams it is possible – through analysis of interference fringes – to quantitatively determine the deformation of the sensors, and thus the deformation of the monitored construction. Applied interferometric sensors belong to a group of sensors with long measuring arms (long-gage sensors), so the measured deformations are the average value for the whole length of the sensor.

## 3 Defects Detection and Localization

In order to estimate the vessel’s technical condition (to detect any kind of critical defects to avoid dangerous situation) the analytical analysis of measured data from sensors is required. It was proposed to analyze local strain distribution inside the composite material and compare it with the numerical model of the strain field for selected value of internal pressure. Any deviations could indicate potential defects. However, the perfect model of composite pressure vessel is always different from the real object. So in order to create real working on-board monitoring system it was decided to calculate an artificial factor, called ABS factor, and compare it with the specified threshold level. The ABS is calculated as an absolute value of the difference between pressure-curve slopes (fig. 2) for a new vessel (without load history) and current measuring state. At the same time it is also possible to compare signals from selected sensors. For a vessel without defects the dependencies between various sensors for the following load cycles should be the same (or very similar). If any defect occurs, then the interdependence between selected sensors will be disturbed.

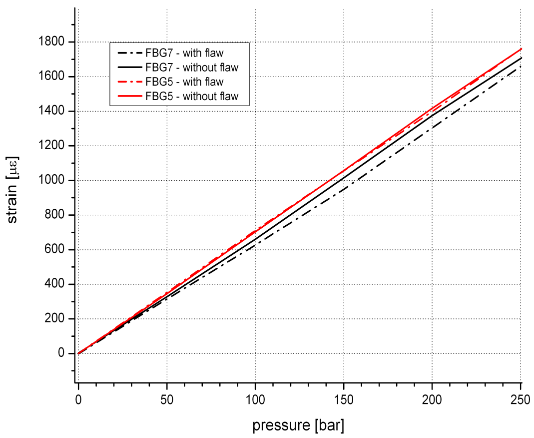



a) b)

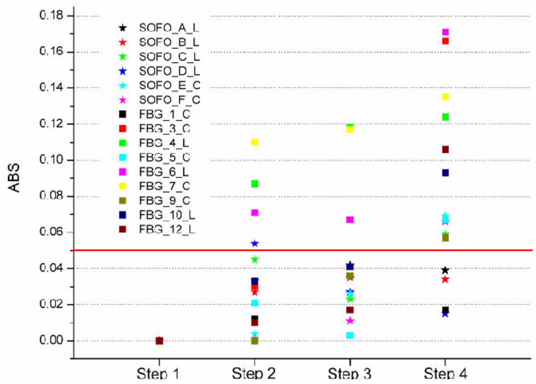
**Figure 2: Exemplary pressure – strain curve (a) for a brand new high pressure composite vessel (without external flaws) [4] and sensors displacement on the vessel surface as well as view of programmed defects - flaws (b) [9].**

Exemplary results analysis of differences in deformation coefficients for a static load test for the vessel with and without defects in the shape of longitudinal and circumferential flaws in the range of 0 to 350 bar were set out in figure 3. The results obtained confirm the assumption that local defecting of the composite material causes local change in the slope coefficient of the curve pressure-deformation, which was expressed by ABS coefficient (absolute value of the slope coefficients difference) [9].

The analysis of the obtained results (Fig. 3) indicates there are perturbations in the strain field of the measured vessel. It is possible to notice that after the first defect was made (Step 2 - flaw in longitudinal direction: 8 cm long, 2 mm deep) almost all the sensors showed different strain values in comparison with the reference measurement (Step 1). The most sensitive for longitudinal defect was the sensor located in the circumferential direction (FBG7). After the next defect was made (Step 3 - flaw in cross direction: 10 cm long, 2 mm deep) changes in strain field distribution were observed. These deformations were clearly registered by longitudinal sensors, especially by fiber Bragg gratings (i.e. FBG4). It arises from fact that SOFO sensors are longer than FBG and average the strain value from whole length of the vessel. FBG sensors are shorter and made the measurements on the comparatively smaller area. In the final step both defects were enlarged (the depth of each was 4.5 mm) and all sensors registered changes in measurands. It is possible to notice that such small defects were earlier indicated by FBG sensors rather than by the SOFO ones. It follows from the length of the sensors in comparison with the defect's length.




a)

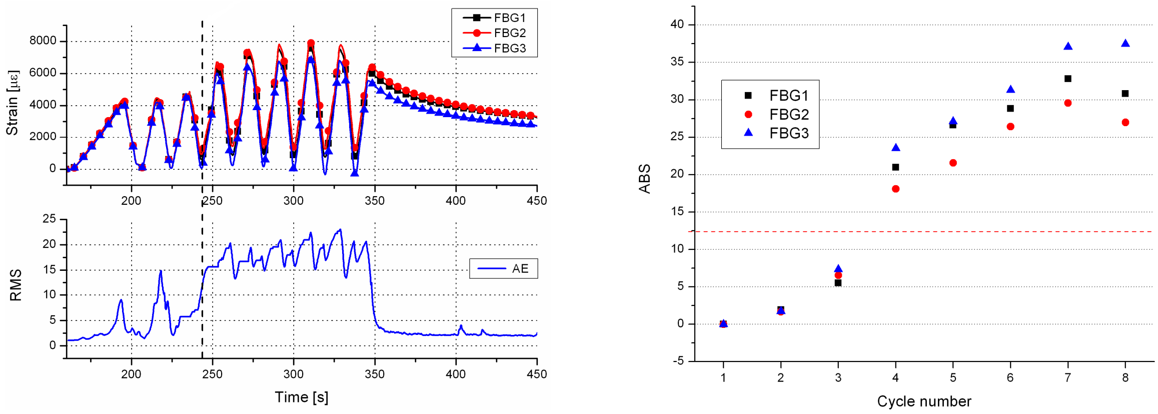



b)

**Figure 3: Exemplary pressure – strain curve for vessel without and with defect in cross direction (after Step 2) measured by selected FBG sensors (a) and analysis of obtained results (b); detection of defects in high pressure vessel without flaw (Step 1) and with various flaws (Step 2 ÷ Step 4) [9].**

In order to check an algorithm of defect detection in real conditions test vessel was put to the cycling test. A prototype high pressure vessel type III (fully wrapped metallic liner) with nominal working pressure 700 bar was cycled in a pressure range from 20 to 875 bar and about 700 cycles were accomplished.

Figure 4a (upper graph) shows the local strains in the circumferential direction registered in the destruction moment of the vessel and corresponding to that event signals from Acoustic Emission sensors (lower graph). It is worth noting that the damage to the vessel (the broken line in fig. 4a) was preceded by a considerable increase in local deformations (of the order of 1500 ÷ 3000 $\mu\varepsilon$) observed in various points of the structure. This was caused by the steel liner under the strengthening composite layer getting leaky. It is also possible to observe a fine correlation between the increase in RMS signal (from AE), which testifies to the high level of the damage to the composite material, as well as increase in local strains registered by FBGs [9].




a) b)

**Figure 4: Local strains (a) registered by FBGs in circumferential direction (upper graph) as well as signal from AE (lower graph) in the destruction moment and analysis of obtained results – detection of defect in a high pressure vessel (b) [5].**

In Figure 4b there is an analysis of strain values measured in the last 8 cycles presented. As was described earlier, for each of the pressure-strain characteristics measured by FBG sensor, the curve slope was calculated and compared with reference one. The analysis of ABS for each of the sensors indicates there are perturbations in the strain field of the tested vessel. It is worth noticing that after cycle no. 3 (damage beginning) an ABS coefficient increased meaningfully. It indicates dangerous situation in a high pressure vessel [5].

## 4 Summary

Fiber optic sensor technology offers the possibility of implementing “nervous systems” for infrastructure elements that allow health and damage assessment. In the present work Fiber Bragg Gratings used in measurements give information on local strain values of the composite layer of the vessel caused by internal pressure. This relationship is of linear character. SOFO sensors are longer than FBG ones and average the strain value from the whole surface of the vessel.

For the purpose of monitoring the condition of the entire vessel one should carry out a comparative analysis of the deformations measured at different points. Pressure (static) tests conducted for the vessel with local defects point to the distortion of the symmetry of the strain field resulting from composite discontinuity of the carrying layer. The cyclic tests of steel liner based on the high pressure vessel showed that during cycling there is a significant increase in strain before damage. The experiments with defected vessels and proposed sensors configuration showed that monitoring system based on Fiber Bragg Gratings is more sensitive to defects that occur than SOFO ® one. It is possible to detect the defects (flaws) in the earlier stage.

In spite of essential differences between selected measurement techniques: FBG (short gage sensor - local measurements) and interferometric SOFO® (long gage sensor – average value), both of presented OFS methods can be useful for monitoring and comparing obtained results with numerical model of high pressure composite vessels for hydrogen storage.

In the present work optimization of the number and arrangement of the sensors was not considered. This problem is very complicated and currently is investigated in a few research centers. It should be assumed that in the future applications of high pressure composite tanks for gaseous fuels storage signals from optical fiber based sensors (like: strain, temperature, damage accumulation) will be compared with results from numerical modeling. It means that for each type of vessel a mathematical model of strain field distribution and damage accumulation for each tank and each geometry of the composite structure will be created.

## References


[1] Degrieck J., De Waele W., Verleysen P.: Monitoring of fibre reinforced composites with embedded optical fibre Bragg sensors, with application to filament wound pressure vessels NDT&E International 34, pp. 289-296, 2001.

[2] Kanga D.H., Kimb C.U., Kimc C.G.: The embedment of fiber Bragg grating sensors into filament wound pressure tanks considering multiplexing, NDT&E International 39, pp. 109–116, 2006.

[3] Blazejewski W., Gasior P., Kaleta J., Sankowska A.: Optical fiber sensors integrated with composite material based constructions. Lightguides and Their Applications III, Proc. SPIE s. 66081L-1-66081L-10, cop. 2007.

[4] Glisic B., Inaudi D.: Health monitoring of a full composite CNG tanks using long-gage fiber optic sensors. 11th SPIE's Annual International Symposium on Smart Structures and Materials, Vol. 5384-7 March 14-18, 2004, San Diego, USA

[5] Gasior P., Kaleta J., Sankowska A.: Optical fiber sensors in health monitoring of composite high pressure vessels for hydrogen, Proc. SPIE s. 66163G-1-66163G-10, cop. 2007.

[6] F. Yu, S. Yin, Fiber Optic Sensors, Marcel Dekker, Inc., New York, 2002.

[7] Inaudi D., et al., Low-coherence deformation sensors for the monitoring of civil engineering structures, Sensors and Actuators, A 44, 1994, pp. 125-130.

[8] Glisic B., Inaudi D.: Fibre Optic Methods for Structural Health Monitoring. John Wiley and Sons Ltd, The Atrium, Southern Gate, Chichester, 2007.

[9] Blazejewski W., Gasior P., Kaleta J., Sankowska A..: Optical Fiber Sensors as NDT methods for strain state monitoring of high pressure composites vessels. Comparison of different types of OFS. 8th International Conference on Durability of Composite Systems, 16-18 July 2008, Porto, Portugal.

# AppliedSensor FE Hydrogen Sensor

**Miodrag Kosovic, Niclas Edvardsson,** AppliedSensor Sweden AB, Sweden

## 1 Introduction

In the past 5 years AppliedSensor has been appointed by various automotive OEMs and joint ventures to develop selective hydrogen safety and control sensors for their fuel cells and related FC vehicles [1]. Key requirements were plain selectivity to $H_2$, speed of response < 1s and no need for recalibration throughout the entire lifetime. All this at automotive standards. During a 3-year development AppliedSensor has achieved all above and is now supplying said customer's fleets.

## 2 AppliedSensor FE Hydrogen Sensor

The AppliedSensor hydrogen sensor uses a sensor component (SC) based on a field-effect (FE) transistor with a catalytic metal stack as the gas-sensing layer [2]. This semiconductor technology approach offers a low cost sensor component based on a well established and reliable high volume technology with excellent sensor properties including high-speed response and outstanding selectivity.

## 3 The Hydrogen Sensor Component

AppliedSensor offers hydrogen sensor components for different applications using different types of sensitive layers, where one is specially optimized for detection of hydrogen concentrations in the 0-10% range, which can be achieved by using two different response mechanisms [3]. The combination of response mechanisms enables hydrogen predictions with good selectivity over a large hydrogen concentration range.

A calibration curve for the 1-5 % $H_2$ concentration range is shown below.

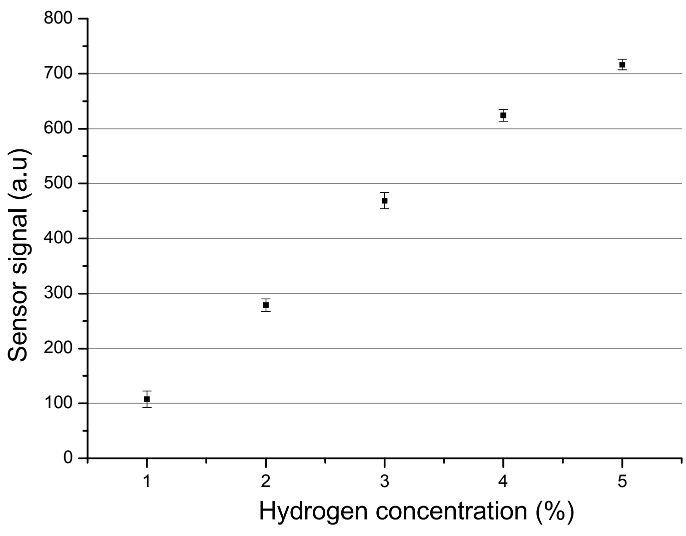



**Figure 1: Calibration curve for the 1-5 % $H_2$ concentration range.**

# 4 Operating Principles

## 4.1 The transducer

The basis for the sensor is the Field Effect transistor operating in diode-coupled mode. The gas sensitive properties are achieved by depositing a catalytic metal stack as the gate of the device. Through the chemical reactions during hydrogen exposure, the I-V characteristics of the device will shift as shown in the figure below. Operating at a constant current, the response is recorded as a change of the voltage (ΔV) over the device.

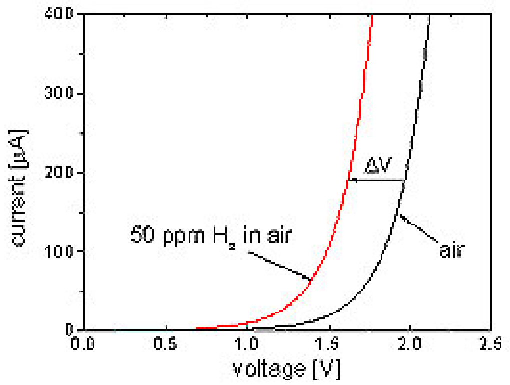



**Figure 2a: The effect on the I-V characteristics of the Field Effect transistor due to hydrogen exposure.**

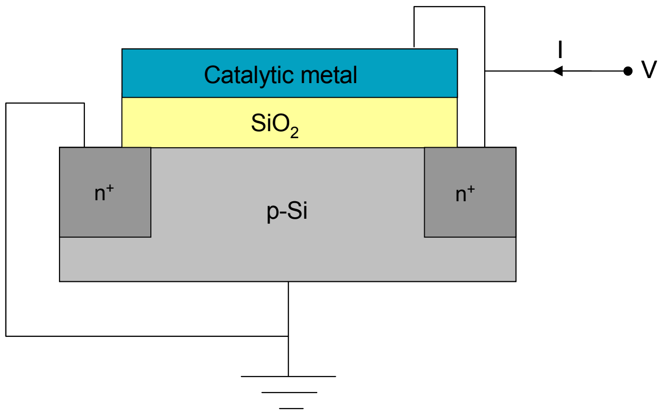



**Figure 2b: Operation of Field Effect transistor in diode-coupled mode.**

## 4.2 The field effect (FE) response mechanism

The dominating chemical reactions that give rise to the sensing properties are as follows: Hydrogen gas ($H_2$) will adsorb and dissociate into hydrogen atoms on the surface of the catalytic metal stack. The hydrogen atoms will be transported through the metal down to the metal-insulator interface resulting in an effective dipole layer at the interface. The effective dipole layer will in turn give rise to a potential drop over the interface, affecting the transistor in the same way as if the gate bias had been changed, i.e. shifting the I-V curve. Hence, the actual sensing part of the device is the metal-insulator interface, which is accessible only to hydrogen atoms and thereby gives excellent selectivity and robustness. The back-reactions include transportation of hydrogen from the interface to the surface and water formation ($2H + O \rightarrow H_2O$). The steady-state point between all the reactions is dependent on the actual hydrogen gas concentration in the ambient.

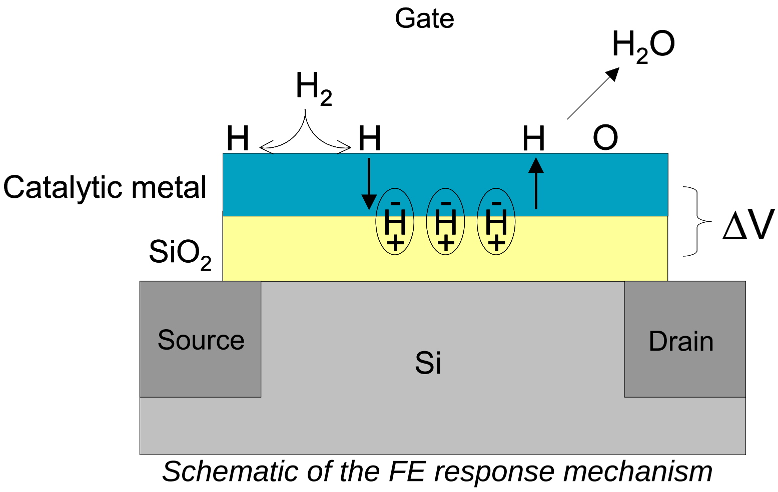



**Figure 3: Schematic of the FE response mechanism.**

### 4.3 The thermal conductivity (TC) response mechanism

$H_2$ is the gas with the highest cooling efficiency, i.e., it has the highest thermal conductivity. The high thermal conductivity as well as a large difference to most other gases is used for measurement purposes. The fact that the thermal conductivity for $H_2$ is almost 7 times larger than for air allows fairly small amounts of $H_2$ in air to be detected and quantified. The sensor component is operated at elevated temperature, which permits that the heat exchange between the sensor component and the colder ambient to be monitored. Hence, also the thermal conductivity of the test gas (ambient) can be measured. The $H_2$ concentration can be determined if a calibration at known conditions has been performed.

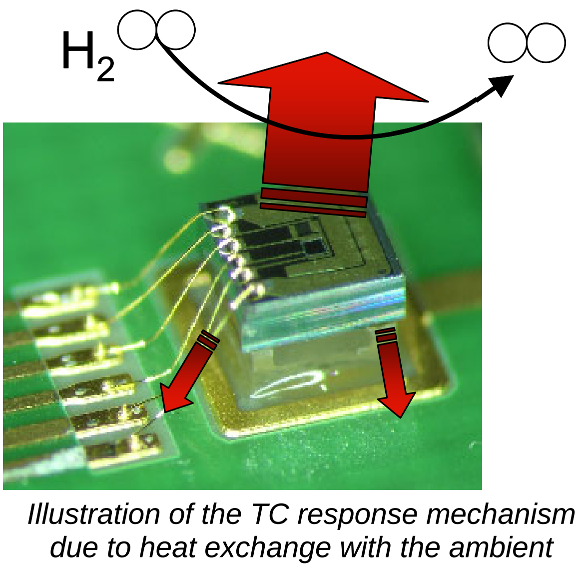



**Figure 4: TC response mechanism.**

## 5 Signal Processing and Data Analysis

The signal processing (algorithms) is an essential part of the AppliedSensor hydrogen sensor. The main purpose of the signal processing is to convert the available sensor signals into an output signal indicating the current $H_2$ concentration. Also, the sensor components suffer from some imperfections, which must be compensated for in order to fulfil the high accuracy demands for the sensor. The two main signals entering the algorithm for further processing are the TC signal and the FE signal. The TC signal is related to the heat conductance of surrounding ambient, whereas a high $H_2$ concentration will result in a larger signal than the signal of a hydrogen-free environment. The TC signal has best signal to noise properties for higher $H_2$ concentrations. The FE signal indicates $H_2$ variations accurately at lower concentrations, and becomes saturated for higher concentrations. The information from the sensor signals is thus partly overlapping and partly complementary. To utilize the available information from the two sensor signals maximally, the sensor signals are weighted in different concentration intervals according to their relative importance. The weighted signals are then converted into a $H_2$ concentration via a transformation. To compensate the sensor-to-sensor variation, each sensor is individually calibrated, where the FE-TC weighting and the $H_2$ prediction model are optimized.

## 6 Features and Benefits

Among many others the key advantages of the AppliedSensor hydrogen sensor product line lies in the following benefits:

### 6.1 Competitive price using standard silicon process and COB packaging

The component can be easily mass-produced in a standard silicon process foundry. The small chip size yields a very high number of sensors per wafer, leading to low production costs per unit. Another cost advantage of using a standard silicon process is that existing tools for Wafer Level Testing (WLT) can be used to achieve quality management on a component level early in production. Furthermore, AppliedSensor was first to introduce chip-on-board (COB) packaging for gas sensors – a major cost-reducing factor at component level.

### 6.2 Excellent selectivity to hydrogen

Using a high level of control in metal deposition, the AppliedSensor FE sensor can achieve near perfect selectivity to hydrogen without cross interference from gases such as CO, $CO_2$, NOx, hydrocarbons or ammonia, as shown in the chart below. Importantly, our sensors show no response to humidity.

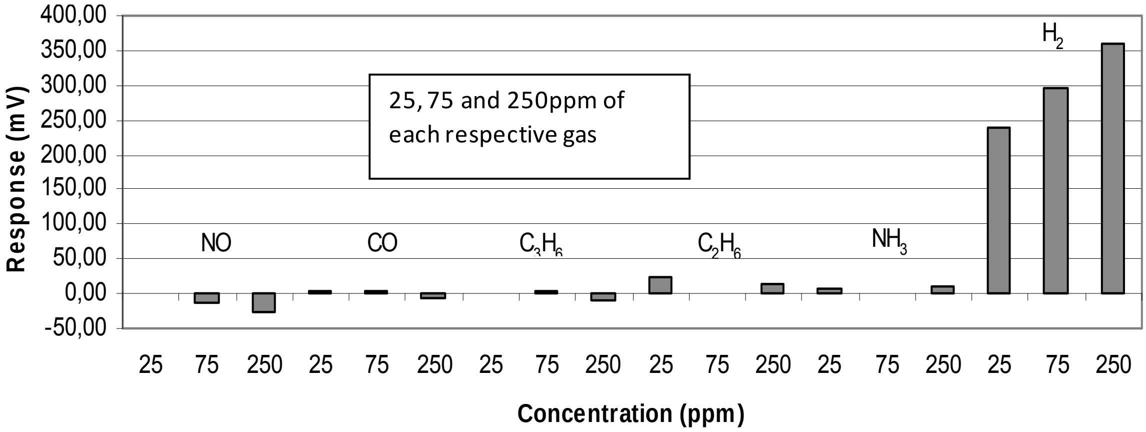



**Figure 4: Response=f (concentration).**

The AppliedSensor FE sensor shows excellent selectivity

### 6.3 Speed of response

At elevated operating temperature, the speed of response is in the order of a few seconds. Using data evaluation algorithms the speed of response can be further lowered to less than 3 seconds.

## 7 Available Products

AppliedSensor are offering following products with various configurations to different market segments.

### 7.1 Fast and highly selective

The AppliedSensor HLS-440A10 Hydrogen Leak Sensor is an accurate, fast-responding sensor designed for installation in vehicles and hydrogen fuelling stations [4]. Unlike sensors that can be extremely cross sensitive to a variety of combustible gases, AppliedSensor's HLS-440A10 sensor was developed using advancements in Field Effect (FE) technology. This enables it to be highly selective to hydrogen gas without interference from background gases or water vapour.

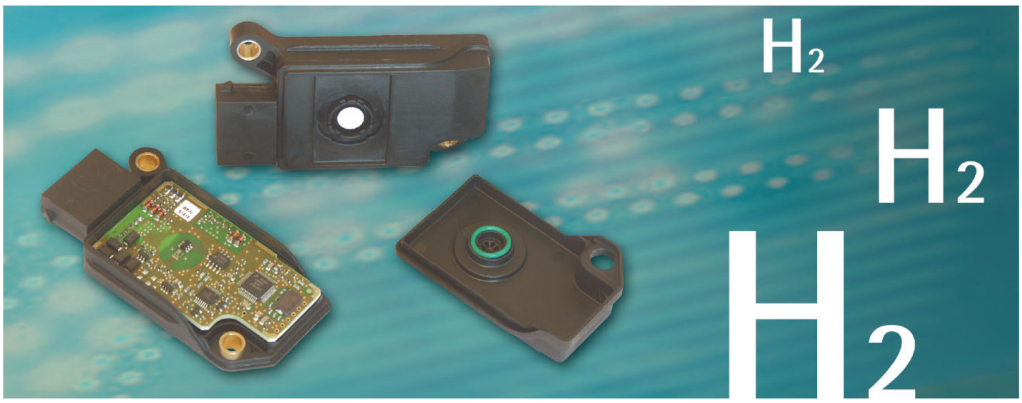



**Figure 5: HLS-440 - Hydrogen Leak Sensor.**

### 7.2 Fast and highly selective

The AppliedSensor HSS-440P Hydrogen Process Sensor is an accurate, fast-responding sensor designed for installation in harsh environments such as for example fuel cell exhausts [5]. The sensor will measure hydrogen in the range of 0-10% in air or nitrogen.

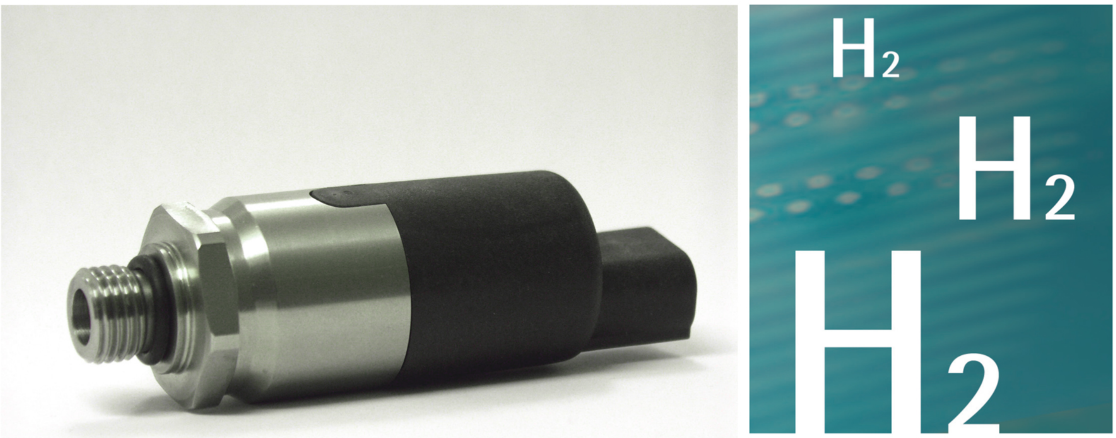



**Figure 6: HSS-440P - Hydrogen Process Sensor.**

### 7.3 Tough and resistant

The HSS-440P Hydrogen Process Sensor will provide hydrogen detection and measurement for applications where conditions are harsh. With an IP6K9 rating and designed towards Atex Zone 2 it can be installed almost anywhere.

### 7.4 Fast and highly selective

The AppliedSensor HPS-100 Hydrogen Process Sensor is an accurate, fast-responding sensor designed for installation in harsh environments such as for example fuel cells [6]. The sensor will measure hydrogen in the range of 0-100% and will function up to 3 bar(a)

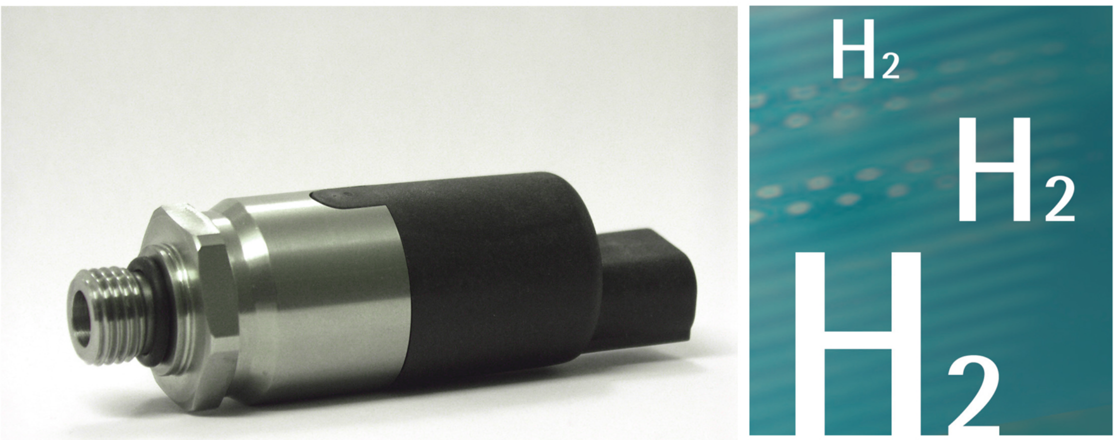



**Figure 7: HPS-100 - Hydrogen Process Sensor.**

### 7.5 Tough and resistant

The HPS-100 Hydrogen Process Sensor will provide hydrogen detection and measurement for applications where conditions are harsh. With an IP6K9 rating and designed towards Atex Zone 2 it can be installed almost anywhere.

### References

[1] Wasserstoffsensor zur Leckagedetektion im Automobil by Michael Hackenberg, Jürgen Kappler, Miodrag Kosovic, Niclas Edvardsson, Tomas Eklov, Pär Back in Sensoren im Automobil II (expert-Verlag, ISBN: 3816927505), 49 –63 (2007).

[2] I. Lundström, M. S. Shivaraman, and C. M. Svensson, Journal of Applied Fhysics 46, 3876 (1975).

[3] FE Sensor Technology presentation: http://appliedsensor.com/pdfs/APS_FE%20Sensor_1109.pdf

[4] HLS-440 Data sheet: http://appliedsensor.com/pdfs/HLS-440_1009.pdf

[5] HLS-440P Data sheet: http://appliedsensor.com/pdfs/HLS-440P_0410.pdf

[6] HPS-100 Data sheet: http://appliedsensor.com/pdfs/HPS-100_0410.pdf

# Risk Associated with the Use of Barriers in Hydrogen Refueling Stations

**Jeffrey LaChance**, **Jesse Phillips**, **William Houf**, Sandia National Laboratories*, USA

## 1 Introduction

Separation distances are used in hydrogen refueling stations to protect people, structures, and equipment from the consequences of accidental hydrogen releases. Specifically, hydrogen jet flames resulting from ignition of unintended releases can be extensive in length and pose significant radiation and impingement hazards. Depending on the leak diameter and source pressure, the resulting separation distances can be unacceptably large. One possible mitigation strategy to reduce exposure to jet flames is to incorporate barriers around hydrogen storage, process piping, and delivery equipment. The effectiveness of barrier walls to reduce hazards at hydrogen facilities has been previously evaluated using experimental and modeling information developed at Sandia National Laboratories (Houf, et.al. 2008). The effect of barriers on the risk from different types of hazards including direct flame contact, radiation heat fluxes, and overpressures associated with delayed hydrogen ignition has subsequently been evaluated and used to identify potential reductions in separation distances in hydrogen facilities. Both the frequency and consequences used in this risk assessment and the risk results are described. The results of the barrier risk analysis can also be used to help establish risk-informed barrier design requirements for use in hydrogen codes and standards.

## 2 Barrier Effects on Consequences

Barrier walls will reduce the extent of unacceptable consequences due to hydrogen releases resulting from accidents involving high-pressure equipment. While reducing the extent of hydrogen jets, the walls may introduce other hazards if not properly configured. The configuration considerations include the height and width of the barrier as well as the structural strength of the wall. The potential consequences from hydrogen releases behind barriers are discussed in this section.

## 3 Direct Flame Effects

The presence of barriers will block a significant fraction of jet fires resulting from immediate ignition of hydrogen releases. Barriers that are higher than 2.4m will provide protection from direct flame contact for individuals on the protected side of the barrier (i.e., downstream of the barrier). Sufficiently high barriers are required to protect people at ground level from jet fires that may skim the top of barrier. In addition, the barriers must be wide enough to

---

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94-AL85000.

prevent exposure from jets resulting from leaks in all the hydrogen components. A three-wall barrier that encompasses the hydrogen components can be particularly effective in preventing exposure to jet fires. However, vertical barriers will deflect some jet fires down and back towards the hydrogen facility located upstream of the barrier resulting in a wider area of exposure for personnel who may be working on the facility and potentially resulting in additional component failures. Tilting the barrier at some angle will help reduce this effect.

As illustrated in Figure 1, an unignited hydrogen jet will be confined to a region essentially upstream of the barriers, greatly reducing the downstream (axial) extent of the unignited release as compared to the case with no barrier. A calculation of the horizontal extent of the concentration decay for a free jet by Houf and Schefer, 2007 indicates that the 8% mole fraction surface would extend 10.4 m from the jet exit while the 4% mole fraction surface would extend approximately 20.8m. With a vertical wall barrier, the extent of the 4% and 8% mole fraction surfaces are 3.2 m and 1.9 m, respectively from the jet nozzle. The surfaces in Figure 1 were calculated (Houf et al., 2008) using the FUEGO computer program developed by Sandia (Moen et al., 2002) for a 3.175 mm diameter leak at 10.3 MPa directed at the center of a 2.4m x 2.4m barrier and located 1.22 m away from the wall at a height of 1.22 m.

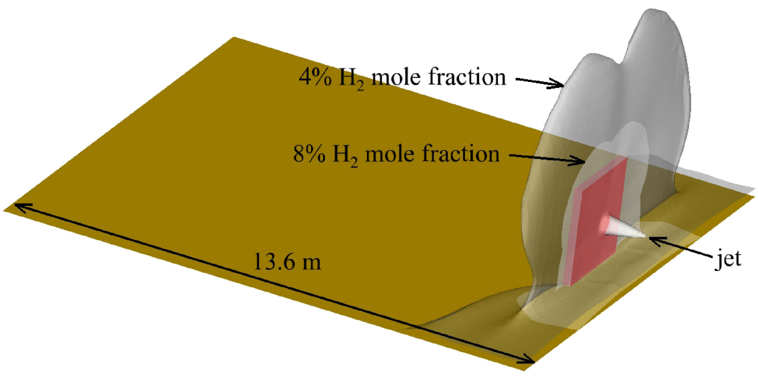



**Figure 1: Illustration of the effect of barriers on unignited hydrogen envelopes.**

## 4 Thermal Radiation Effects

Although a barrier may prevent direct contact to the flames from a jet fire, there is still a potential to be harmed by the thermal radiation from the ignited jet. Fortunately, the use of a barrier also reduces the percentage of hydrogen jet flames that can result in thermal radiation exposures to individuals. For those flames that hit the barrier, the flame will be redirected and reshaped by the barrier. The portion of the flame that extends over and around the barrier will result in radiation to individuals on the other side of the barrier. For flames that are directed over the wall, the portions of the flame not blocked by the wall can result in radiation to individuals on the other side of the barrier.

Houf et al., 2008 have performed experimental and analytical work to evaluate the impact of barriers when the jets hit the barriers. The analytical results indicate that barriers will significantly reduce the axially extent of a specific radiation heat flux level by roughly a factor of 3. As indicated in Figure 2, a vertical barrier will substantially reduce the axial extent of a 4.7 kW/m$^2$ isosurface (i.e., in the direction of the jet). However, the extent of the isosurface in the lateral and vertical directions parallel to the barrier is greater than for a free jet with no barrier.

The residual risk from flames that are directed above the top of a barrier can be eliminated by proper selection of the barrier height and distance from the hydrogen components. This can be illustrated using the model developed by Houf and Schefer, 2007 and the geometry shown in Figure 3.

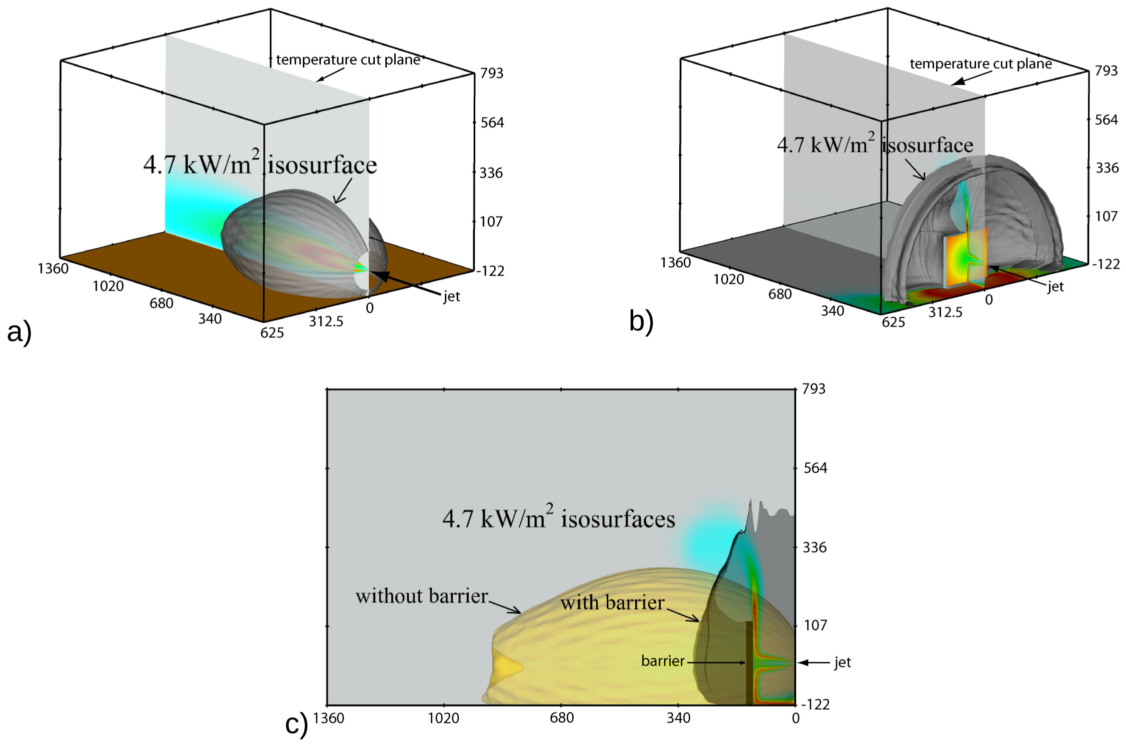



**Figure 2: Calculated isosurfaces for a thermal radiation heat flux of 4.7 kW/m$^2$ from hydrogen jet flames; (a) free jet flame with ground plane; (b) jet flame directed toward center of 1-wall vertical barrier; (c) side view of isosurfaces shown in (a) and (b), comparing horizontal and vertical extent of radiation field without and with a barrier; jet flow is from right to left with distances in centimeters.**

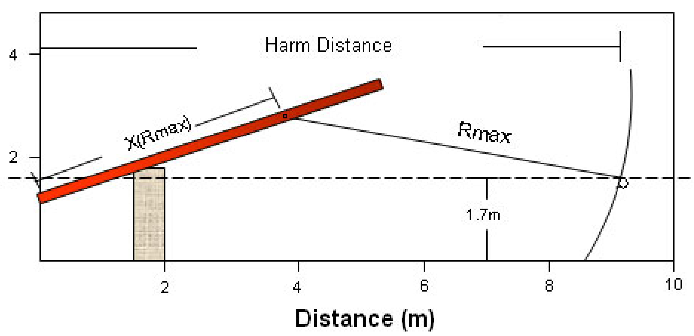



**Figure 3: Illustration of flame-barrier orientation resulting in thermal radiation exposure.**

To determine an approximate harm distance based on a thermal radiation heat flux when the flame passes over the top of the barrier, an arc of radius $R_{max}$, the maximum radius for a given heat flux level, originating from the axial location on the flame where the maximum heat flux occurs (designated as $X(R_{max})$ was drawn. $R_{max}$ was calculated as the separation distance minus the $X(R_{max})$, roughly 0.7 times the flame length. A correlation for separation distance was available from prior work by Houf and Schefer, 2007. The intersection of this arc with y=1.7m, the height of an individual's head, was taken as the harm distance associated with a heat flux from a flame that passes over the top of the barrier.

A review of the geometry in Figure 3 indicates that increasing the angle between the flame and the barrier will increase the physical distance between an individual and the flame, thus reducing the distance $R_{max}$ associated with a selected heat flux level. This angle can be increased by locating the wall closer to the equipment, increasing the wall height, or both. Figure 4 depicts an approximation for the decrease in harm distances for three heat flux levels as the angle of the flame is increased. There are several important points pertaining to this figure. First, flames with shallow angles will not substantially reduce the harm distance. Harm distance only begins to substantially decrease when the flames have angles greater than approximately 30 degrees. Second, there is an angle at which a given heat flux level will not occur at a target on the other side of the wall. For the 4.7 kW/m$^2$ heat flux level shown in Figure 4, that angle is 46 degrees. This implies that the orientation of the barrier and hydrogen source can be selected to ensure that a target will not be exposed to a selected heat flux level. An example of such an orientation involves selecting a very high wall height.

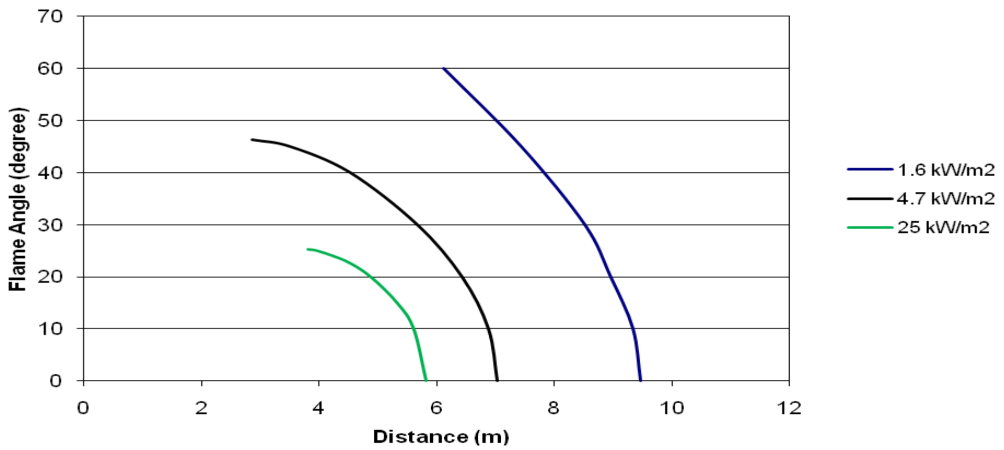
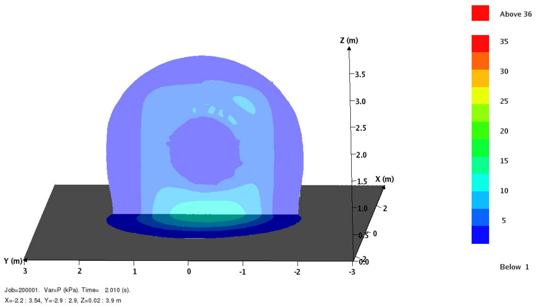


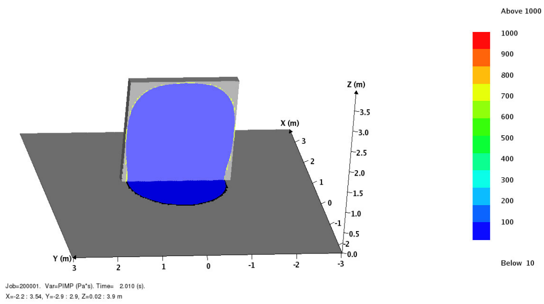

**Figure 4: Separation distances for radiation heat fluxes from hydrogen jets orientated at various angles.**

## 5 Pressure Effects

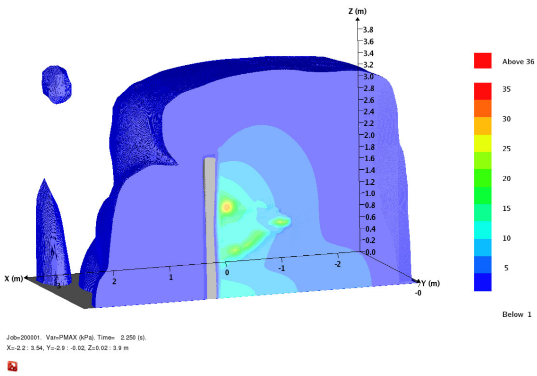
A potentially negative consequence related to the use of barriers is the increase in pressure resulting from a delayed ignition of hydrogen confined behind the barrier. The resulting overpressure may harm individuals on either side of the wall or cause failure of the barrier. These possibilities were analytically evaluated by Houf et al., 2008 for various release pressures, leak diameters, and ignition times using the FLACS (2009) Navier-Stokes code. Although the peak overpressures that were reported in Houf et al., 2008 could be relatively high (e.g., 65 kPa for a 9.09 mm leak at 1.83 MPa with ignition occurring at 2 seconds after initiation of the leak), these overpressures are very localized. Figure 5 provides an illustration of the overpressure and pressure impulse profiles on the entire barrier wall evaluated for a 3.28 mm leak in a 20.8 MPa system ignited at 2 seconds. The pressure increase on the wall is between 5 and 10 kPa and the pressure impulse is approximately 100 and 200 Pa-s. Similar results were obtained for a delayed ignition of a leak in a 103.5 MPa system. These types of overpressures and pressure impulses would only cause minor damage to reinforced structures or barrier walls (AICE, 1994).



a)



b)



c)

**Figure 5: FLACS results for a 3.28 mm leak in a 20.8 MPa system ignited at 2 seconds, (a) pressure on wall, (b) pressure impulse on wall, and (c) maximum pressure contour on both sides of the wall.**

Figure 5 also illustrates the maximum pressure predicted to occur on both sides of the barrier. Upstream of the barrier, the maximum overpressures are between 10 and 15 kPa and downstream of the barrier the pressures are only between 1 to 2 kPa. These types of pressures would not cause any direct harm to a person (Jeffries et al., 1997).

## 6 Risk Evaluation

As indicated in the previous discussion, the use of properly designed barriers will remove the potential for direct contact with jet flames, reduce the distance of unignited jets, reduce the isosurfaces for various thermal radiation heat fluxes, and not result in any substantial increase in pressure that would harm people or structures. Thus, barriers provide a means to reduce the risk to the public from unintended releases of hydrogen. This reduction in risk also allows for the opportunity to reduce the separation distances at a hydrogen facility. Estimates of the risk reduction potential were generated by Sandia using the risk model generated for evaluation of the separation distances selected for incorporation into the NFPA-2 and NFPA-55 hydrogen standards (LaChance et al., 2009) and the consequence results reported in Houf et al., 2008. The system configurations and associated leakage frequencies utilized in LaChance et al., 2009 were utilized in the barrier risk assessment, thus allowing for direct comparison of the risk with and without a barrier. The barrier wall was assumed to be 2.4 m high and separated from the hydrogen equipment by 1.22 m Table 1 provides a comparison of the risk to an individual located at the facility lot line.

**Table 1: Estimated risk reduction from the use of barriers.**

| System Pressure (MPa) | Leak Diameter[1] (mm) | Separation Distance to Facility Lot Line[2] w/o Barrier (m) | Individual Risk at Facility Lot Line (fatalities /yr) | |
|---|---|---|---|---|
| | | | w/o Barrier | Barrier |
| 1.83 | 9.09 | 14.0 | 2.0E-5 | 5.4E-6 |
| 20.78 | 3.28 | 14.0 | 2.1E-5 | 5.5E-6 |
| 51.81 | 1.37 | 8.8 | 3.6E-5 | 1.1E-5 |
| 103.52 | 1.24 | 10.4 | 3.5E-5 | 1.0E-5 |

[1] Leak diameter corresponds to 3% of the largest flow area in the system
[2] Separation distance specified in NFPA-55, based on selected leak diameter.

As indicated in Table 1, the presence of a barrier can be used to reduce the risk to a person standing at the facility lot line. The use of a barrier can also be used to reduce the separation distances. For a risk level equivalent to the risk without a barrier, the separation distance to the facility lot line can be shortened to approximately 3.5 m (measured from edge of the facility and not the barrier). The separation distance from the barrier for the example facilities would be approximately 2 m.

**Acknowledgements**

This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program under the Codes and Standards subprogram element managed by Antonio Ruiz.

**References**

[1] AICE, “Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs,” Center for Chemical Process Safety, American Institute of Chemical Engineers, 1998.

[2] FLACS Version 9.1 User’s Manual, GEXCON, Bergen, Norway, November 2009.

[3] Houf, W., Schefer, R., and Evans, G., “Analysis of Barriers for Mitigation of Unintended Releases of Hydrogen,” Presented at the Annual Hydrogen Conference and Hydrogen Expo USA, March 30 – April 3, 2008.

[4] Houf, W. and Schefer, R.,, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," Int. Journal of Hydrogen Energy, Vol. 32, 136-151, January 2007.

[5] Jeffries, R.M., Hunt, S.J., and Gould, L., "Derivation of Fatality of Probability Function for Occupant Buildings Subject to Blast Loads," Health & Safety Executive, 1997.

[6] LaChance, J., Houf, W., Middleton, B., Fluer, L., "Analysis to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards," Sandia Report SAND2009-0874, March 2009.

[7] Moen, C.D., Evans, G.H., Domino, S.P. and Burns, S.P., "A Multi-Mechanics Approach to Computational Heat Transfer," Proceedings 2002 ASME Int. Mech. Eng. Congress and Exhibition, New Orleans, IMECE2002-33098, November 17-22, 2002.

SI Safety Issues

SI.1 Vehicle and Infrastructural Safety

SI.2 Regulations, Codes, Standards and Test Methods

# Advancing Commercialization of Hydrogen and Fuel Cell Technologies Through International Cooperation of Regulations, Codes, and Standards (RCS)

Randy Dey

**Abstract**

This chapter discusses the importance of international cooperation in the development of regulations, codes, and standards on hydrogen and fuel cell technologies. To facilitate commercialization of these new technologies, it is essential to remove non-tariff barriers by harmonizing regulations, codes, and standards to facilitate global trade.

# Regulations, Codes & Standards for the Approval of Hydrogen Refuelling Stations

**Reinhold Wurster**, Ludwig-Bölkow-Systemtechnik GmbH, Germany
**Gerd Petra Haugom**, Det Norske Veritas AS, Cleaner Energy
**Tom Elliger**, TÜV SÜD Industrie Service GmbH, Germany

## 1 Introduction

In several world regions, the roll out of commercial hydrogen fuel cell vehicles is expected to gain momentum from 2015 onwards. Germany and Japan have announced the stepwise implementation of Hydrogen Refuelling Station (HRS) infrastructures between 2015 and 2020 [1]. In Germany, a joint statement (MoU) on the development and market introduction of electric vehicles with fuel cells was announced by leading automobile manufacturers in September 2009. From 2015 onwards, several hundred thousand vehicles are anticipated worldwide. This started with a joint initiative by Daimler and Linde aimed at providing a sufficient hydrogen refuelling station infrastructure, which is the key to establishing electric vehicles with fuel cells in the market. In addition to Daimler and Linde, OMV, Shell, Total, Vattenfall Europe and EnBW are participating in this endeavour, which is supported by the German government.

This paper discusses the state of affairs regarding HRS approval.

## 2 What Has Been Achieved?

To successfully facilitate the implementation of a hydrogen infrastructure, local approval conditions have to be respected while applying preferably harmonised minimum requirements for the safe design, operation and maintenance of an HRS as well as a recommended permitting process. In 2007, key partners from Europe, China, Japan and the USA completed the HyApproval Handbook, which serves as a guideline to this approach [2].

Furthermore, ISO has issued a technical specification (TS) for the standardised layout of HRSs, ISO/TS 20100 *Gaseous Hydrogen — Fuelling Stations* [ISO 20100 - 2008], which was prepared by ISO/TC 197 WG11. WG11 is presently conducting further analyses of safety distances and hazardous zones. With regard to safety distances, a task group aims to improve the safety distance table of the current ISO/CD 20100 [3] for each type/category of equipment (e.g. un-/occupied buildings, flammable liquids above-/under-ground, stocks of combustible material, flammable gas storage above ground, the facility lot line, pedestrian walkways, vehicle low-speed passageways, roadways, high voltage and other overhead power lines) using a risk-informed rationale. This is considered quite an innovative approach supported by pre-normative work. If the group is successful, the implementation of a risk-based decision approach will allow more flexibility in the design of HRSs without compromising the safety of the installations, while new innovative solutions might still be allowed as long as they comply with defined risk-based criteria.

Another task group within ISO/TC 197 WG11 is in the process of defining requirements applicable to the compressor and dispensing system. Their focus is in particular on a dispenser protection table that identifies the safeguards necessary for foreseen equipment malfunctions. This addresses user safety and the protection of the vehicle-based equipment.

ISO/TC 197 is working towards the development and eventual publication in 2012 of an international standard for the layout, operation and maintenance of public outdoor and non-public warehouse HRSs.

In Germany, a guideline, the VdTÜV Merkblatt Druckgas 514 (Technical Information pressurised gas) [4], has been prepared and covers the planning, construction, equipment, erection, relevant certification, commissioning and operation of HRSs and their components for the dispensing of compressed gaseous hydrogen to storage cylinders for the propulsion of hydrogen road vehicles. It also includes electric/electronic requirements as well as responsibilities derived from the German Health and Safety at Work Regulations. This German guideline for the first time harmonises the state-of-the-art technology relevant to the approval procedure in all German federal states.

## 3 Recommendations for Prioritized Actions

As the permitting processes for the local operation of HRSs must comply with legal requirements, an EU-harmonised approach is desired and needs to be developed over the next few years in order to allow implementation in all EU member states from 2015 onwards, based on a comparable state-of-the-art design, and to ensure legal certainty for the operator.

HyApproval’s key recommendation is to develop an EC regulatory framework for HRSs based on the proven combination of *essential requirements*, *harmonised standards*, *notified bodies and national authorities*. This could be most efficiently achieved through the development of an EC Framework Regulation. Such a framework, which allows the key safety issues to be addressed without impeding continued technological developments, would establish a very streamlined EU 27 uniform permitting process. Going a step further, such a framework would allow an HRS “type approval” mechanism (similar to that for road vehicles), permitting a given station design to be approved for widespread deployment in all EU 27 countries.

Until such a framework is fully established at EC level, national authorities are encouraged to support the national players in their work to obtain suitable HRS approval requirements on a global/European level. At the current stage of HRS development, it is strongly recommended that safety assessments are conducted and included as part of the required HRS approval procedure. Safety assessments are necessary to ensure that all relevant site-specific risks are taken into account. The players in the hydrogen field generally want a simple, straightforward approval process that can be applied on a European level. To achieve this, it will be necessary to establish harmonised requirements and approval criteria and preferably to have responsible authorities at a national level. It is recommended that harmonised requirements and approval criteria include requirements to undertake relevant assessments, and that the approval is not based on specific numerical criteria alone. As further developments in HRS solutions are expected in the coming years, it is important that the HRS approval framework allows for these, for example by accepting the use of a risk-based approach to demonstrate that new solutions are as safe and reliable as the standard solutions covered by the framework.

International standards (ISO, IEC), developed on the basis of the essential requirements set out in a regulation, are the framework of choice for developing and providing HRS design rules and criteria allowing HRSs to meet regulatory and permitting requirements.

A link between a regulation and standards will be a key feature of the proposed regulatory framework and therefore close cooperation between the players in both worlds is a prerequisite - for the proper, efficient and flexible functioning of a lean regulation as well as for the mutual understanding of standards and regulatory experts among each others facilitating this cooperation.

## 4 Next Steps

A key recommendation of the HyApproval project and the resulting *HyApproval Handbook* was to develop an EC regulatory framework for HRSs based on the proven combination of *essential requirements* and *harmonised standards,* as for example ISO 20100 tries to provide. The EC Regulation for vehicles using hydrogen No. 79/2009 [5] of the European Parliament and the Council of 14 January 2009 addresses the need for harmonised approval requirements which would allow HRSs to be approved and built across Europe (EC regulation No. 79/2009 on type-approval of hydrogen-powered motor vehicles and amending Directive 2007/46/EC) states in paragraph 16 of the preamble "*Hydrogen-powered vehicles are unlikely to be successful on the market unless adequate filling-station infrastructure is made available in Europe. The Commission should therefore look into suitable measures to support the establishment of a Europe-wide filling-station network for hydrogen-powered vehicles*."

As the roll out of hydrogen vehicles and related HRSs in Germany will start to increase in 2015, the number of stations will grow from some hundreds to more than 1,000 by 2020. These stations will have to be approved within less than one decade. This approval process will be much enhanced if harmonised requirements can be used as a basis. Taking into account the fact that HRSs will have to be approved in other EU27 countries as well, a unified European framework is essential for the successful introduction of hydrogen in the European transport sector.

## References

[1] *„H2 Mobility“ - Gemeinsame Initiative führender Industrieunternehmen zum Aufbau einer Wasserstoffinfrastruktur in Deutschland*, Berlin, 10 September 2009 [http://www.bmvbs.de/Anlage/original_1096793/Memorandum-of-Understanding-mehr-Informationen.pdf]

Joint Press Release of Linde, Daimler, EnBW, NOW, OMV, Shell, Total and Vattenfall: Initiative *"H2 Mobility" - Major companies sign up to hydrogen infrastructure built-up plan in Germany* [http://www.linde-engineering.com/news/en/news09102009.php]

[2] *Handbook for Hydrogen Refuelling Station Approval*, HyApproval Deliverable 2.2, prepared by Air Liquide as leader of an industry and research consortium, 04 June 2008, published at:

[http://www.hyapproval.org/Publications/The_Handbook/HyApproval_Final_Handbook.pdf]

[3] *Gaseous hydrogen — Fuelling stations*, International Standard ISO/CD 20100, ISO TC 197 N 433, Oct. 2009 [http://www.iso.org/iso/catalogue_detail.htm?csnumber=39206]

[4] *Requirements for hydrogen fueling stations [Anforderungen an Wasserstofftankstellen]*, Compressed gases 514, Editor: Verband der TÜV e.V., TÜV Media GmbH, Köln, 2009

[5] *REGULATION (EC) No 79/2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC*, 14 January 2009 [http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:035:0032:0032:EN:PDF]

[6] *COMMISSION REGULATION (EU) No 406/2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles*, 26 April 2010 [http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:122:0001:0107:EN:PDF]

# Methods for Response and Recovery Time Measurement of Hydrogen Sensors

**Grainne Black**, **Lois Brett**, **Pietro Moretto**, European Commission JRC-IE
**Jaroslav Bousek**, Brno University of Technology, Czech Republic

## 1 Introduction

Hydrogen sensors will play an important role in ensuring the safety of a future hydrogen economy and the performance requirements imposed on these devices must be carefully set based on their conditions of use. In determining whether actual sensor performance meets these requirements, the particularities of the test methods used may influence the findings. It is therefore important to optimize and standardize these methods as a means of ensuring the greatest accuracy and consistency possible.

The draft standard for stationary hydrogen detection apparatus, ISO/FDIS 26142 [1], is currently being finalized. It specifies performance requirements and details of methods for the measurement of various performance characteristics, including response and recovery times. The response time, t(x), of a sensor is defined as the interval between the time when an instantaneous variation from clean air to the standard test gas is produced at the sensor and the time when the response reaches a stated percentage (x) of the final indication. This is often reported as t(90), which is the convention adopted in this work. Conversely, the recovery time t(x) is the interval between the time at which an instantaneous variation from the standard test gas to clean air is produced at the sensor and the time when the response reaches a stated percentage (x) of the maximum indication. Recovery times are usually reported as t(10), which is the case here. Sensor response times are particularly important from a safety perspective because they partly determine the speed of safety response, such as evacuation of personnel or activation of shut-off valves. For the purposes of this paper, response and recovery times shall be referred to collectively as “reaction times”.

A number of methods exist for the measurement of reaction times [2,3]. These can be broadly classed as those which make use of flow for gas transport to the sensor and those which rely on diffusion for the exchange of gases. ISO/FDIS 26142 describes two test methods for the measurement of hydrogen sensor reaction times – one flow-based and one diffusion-based. These provided the starting point for the methods tested in this work. The diffusion-based method was modified significantly to produce two variant methods, which were also tested. Thus, the results of tests on four methods for the measurement of sensor reaction times are reported here.

## 2 Experimental

The sensor testing facility at the JRC-IE has been described in detail in the literature [4,5] and has been used extensively for testing of hydrogen sensors [6]. In this work, the facility was developed to allow for reaction time testing as described below. Sensor samples were tested individually and at room temperature (292 K ± 2 K) under dry gas conditions. A calibrated compact gas chromatograph (GC) was used during diffusion-based tests to confirm the hydrogen concentration.

**Flow-through method**: The Flow-through method measures the reaction time under dynamic conditions and relies on the transport of gas to the sensor's sensing element. The set up and method described here are the product of a series of tests during which improvements and optimisations were made to the flow-through method described in Annex B of ISO FDIS 26142 [1].

The sensor being tested was mounted on a flange above a hole drilled in the side of a copper pipe. Synthetic air or test gas was selectively flowed through the pipe by means of a 3-way valve. Variations on the ISO method involved changing the diameter of the hole and the diameter and geometry of the pipe. Optimum results were obtained using a circular pipe with an internal diameter of 4 mm and gas flow rates between 50–120 sccm. A short section of the circular pipe was replaced by a rectangular part with internal dimensions $12\times3$ mm and the sensor support flange was attached to this section. Use of this rectangular pipe section with a larger cross sectional area significantly reduced gas flow disturbances and pressure fluctuations in the system and also resulted in a cleaner sensor output signal.

**Membrane method:** The Membrane method measures the response time of sensors under static conditions and relies on the diffusion of test gas to the sensor's sensing element. The set up used for these tests is based on that described in Annex A of ISO FDIS 26142 [1] and on the work of Sawaguchi et al. [2]. An aluminium box with an internal volume of 30L was used, inside of which a small aluminium holder housed the sensor under test. The sensor was mounted inside the sensor holder which was sealed with a natural latex membrane, tautly stretched over a 'ridge' on the holder rim and sealed in place with tape. The sensor holder was positioned in the diffusion chamber on a movable metal stand. The desired quantity of hydrogen was then injected into the diffusion chamber and mixing was promoted by 2 fans located at the base of the chamber and one at the level of the hydrogen inlet. Following homogenisation of the test gas mixture, as confirmed by GC, the membrane was ruptured by means of a scalpel fixed to the end of a lever, which was manoeuvred from outside the diffusion chamber. The corresponding start time of the experiment was signalled by manually pressing a switch at the point when the membrane ruptured.

**Lid method:** To overcome some of the difficulties experienced when measuring sensor response time using the Membrane method, a number of modifications to the experimental set up and procedure were made, resulting in the development of the Lid method. The latex membrane was replaced by a latched aluminium lid, which was held firmly in place on the sensor holder by a taut elastic band on one side and by a removable clip on the other side. The clip was removed by manipulation of the lever from outside the chamber. This caused the lid to snap off, releasing a micro switch, which generated an electronic signal accurately defining the start time of the experiment. Otherwise all other aspects of the method remained identical to the Membrane method.

**Gate valve method:** The Gate valve method was developed as an alternative to the Membrane and Lid methods with the advantage of being able to measure not only the sensor response time but also the recovery time. As with both previously described methods a sealed 30L aluminium diffusion chamber was used. A smaller chamber (0.39L), used as the sensor holder, was attached to a flange on one face of the diffusion chamber. The two volumes were separated by a fast acting solenoid gate valve.

During response time measurements, the sensor holder was flushed with clean air and the diffusion chamber with test gas. When the desired gas concentration in both volumes was confirmed by GC all flows were stopped. The valve was then opened electronically. This was recorded as two signals corresponding to the gate contact at the start and at the finish of valve opening, which takes 0.4–0.6 s. The start time of the experiment was taken as halfway between the two contact times. A fan was used to direct gas flow from the diffusion chamber towards the sensor. The procedure for carrying out recovery time measurements was identical to this, except that in these tests the diffusion box was filled with clean air, while the sensor holder was filled with test gas.

**Sensors:** Two commercial sensors were chosen to evaluate the four test methods. The first is a MOSFET sensor capable of measuring hydrogen concentration in the range 0–4.4 vol% hydrogen in air with an accuracy of ± 3000 ppm. The t(90) and t(10) specified by the manufacturer are <3s and <10s respectively. The second sensor is a thermal conductivity sensor (TCD) with a measuring range of 0–100 vol% and an accuracy of ±1 vol%. Both t(90) and t(10) are quoted as <20s, with a typical value of 10s. The reaction times of these sensors were measured at different hydrogen concentrations using all methods except the Membrane method, to highlight any influence this may have on the measurement.

## 3 Results and Discussion

Reaction times were measured over the concentration range 0.5–2 vol% hydrogen and results are shown in Table 1 averaged over all concentrations tested. All response time results are shown graphically in Figs. 1 and 2 for the MOSFET and TCD respectively.

### 3.1 Flow-through method

In the case of response time measurements on the MOSFET sensor, it was found that a plateau often occurred in the response curves. At lower concentrations, this plateau tended to occur before the 90% value had been reached, therefore influencing the measured t(90) and causing greater scatter in the measurements, as shown in Fig. 1. Above 1 vol% hydrogen this scatter is significantly reduced and the apparent influence of concentration disappears. In experiments on the TCD sensor, it was found that the flow rate had an influence on its response. As the flow rate increased, both the zero reading and the reading in hydrogen increased. This may be explained in terms of its mode of operation – the faster the flow the greater the effective thermal conductance of the gas as it cools the heating element. This did not affect the measured reaction times however, as the flow affected the zero reading and the reading in hydrogen equally. No apparent influence of concentration on the response time of the TCD could be discerned. However, considering that the measuring range of this sensor is 0–100 vol% and that tests were performed at a maximum of 2 vol% hydrogen for safety reasons, it is likely that any effect of concentration would not be observed. Interestingly, the measured t(90) is significantly shorter than that given by the manufacturer of 20s and typically <10s.

Recovery time measurements were performed within the same concentration range. No plateau occurred in the sensor signal as it decreased, and so the recovery time results for the MOSFET sensor show less scatter than the response time results, Table 1. A slight steady decrease was observed in the t(10) values with decreasing concentration as fewer hydrogen molecules are required to desorb from the sensor surface. Similar to the response time results, recovery times of the TCD sensor are shorter than stated by the manufacturer and show no influence of concentration within the range tested.

### 3.2 Membrane method

During initial testing, the repeatability of the Membrane method was found to be extremely low, giving an average response time for the MOSFET sensor of 12.8 $\pm$ 12.1s. For this reason, it was used only to test the MOSFET sensor at concentrations of 0.5 and 1 vol% and was modified to give improved repeatability and shorter response times using the Lid method. This lack of repeatability can be principally attributed to lack of consistency in opening of the rubber membrane and to imprecision in marking the start time using the manual switch.

### 3.3 Lid method

The shortest response times for both sensors were measured using the Lid method and these results also show good repeatability. In addition to addressing the difficulties with the Membrane method as outlined above, this method also reduces the potential for diffusion of hydrogen into the sensor holder prior to the start of the experiment. It was found that where the sensor holder was sealed with the rubber membrane, diffusion of hydrogen occurred after 315s, as indicated by a non-zero sensor signal. When the membrane was replaced with the metal lid, diffusion into the sensor holder was found to occur after 1200s.

### 3.4 Gate valve method

The Gate valve method was designed in order to allow for recovery time measurement using a diffusion-based method. However, in the case of the MOSFET sensor, it was found that t(10) could not be measured at concentrations above 1 vol% hydrogen because the final homogenised concentration did not drop below the detection limit of the sensor. The test gas was not replaced by clean air, but instead highly diluted, and although the final concentration had fallen well below 10% of the initial hydrogen concentration, the MOSFET was found to overestimate the hydrogen concentration at such low values, making measurement of t(10) impossible. Recovery time tests were performed on the TCD without difficulty because the experimentally determined detection limit of this sensor is higher than that of the MOSFET, 0.15 vol% versus <0.03 vol%. Response time measurements gave reasonable results, but the necessity of using a fan to direct gas flow towards the sensor raises the possibility of this perpendicular gas flow (as distinct from the parallel flow used in the Flow-through method) influencing the sensor response.

### 3.5 Summary and recommendations

Each method has its own advantages and limitations. The method that results in the shortest response times is the Lid method, which also demonstrates good repeatability and is therefore recommended for response time measurement. However, the Flow-through method is recommended for recovery time measurement as it is the only method in which the test gas is really switched to clean air rather than being highly diluted.

**Table 1: Average response and recovery times using the 4 test methods.**

| Method | MOSFET t(90) | | MOSFET t(10) | | TCD t(90) | | TCD t(10) | |
|---|---|---|---|---|---|---|---|---|
| | Average | σ | Average | σ | Average | σ | Average | σ |
| Flow through | 4.4 | 1.2 | 10.2 | 0.7 | 5.2 | 0.6 | 9.7 | 2.0 |
| Membrane | 12.8 | 12.1 | – | – | – | – | – | – |
| Lid | 2.3 | 0.3 | – | – | 3.6 | 0.8 | – | – |
| Gate valve | 3.0 | 1.2 | 9.2 | 2.6 | 5.2 | 1.2 | 5.3 | 1.2 |

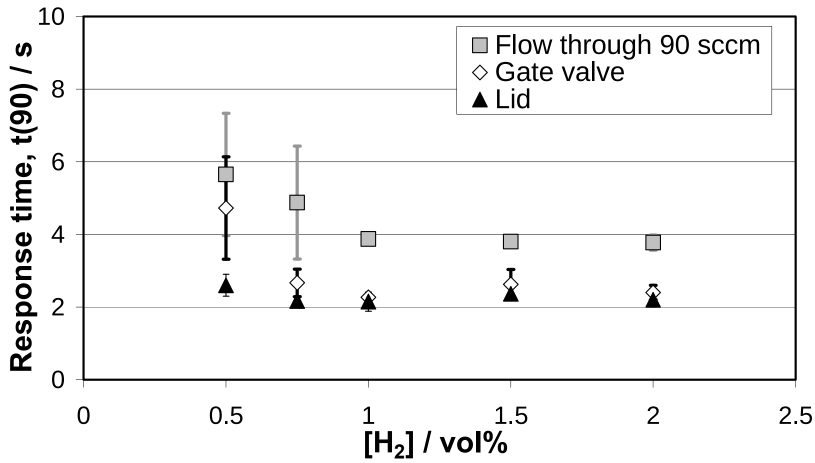



**Figure 1: Average response time of MOSFET sensor using three test methods; error bars represent standard deviation. Membrane results omitted for clarity.**

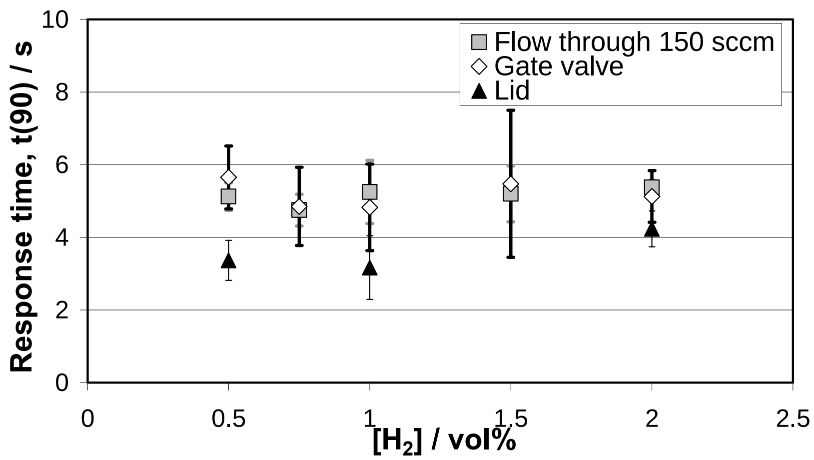



**Figure 2: Average response time of TCD sensor using three test methods; error bars represent standard deviation. Membrane results omitted for clarity.**

**Resferences**

[1] ISO/FDIS 26142 Hydrogen detection apparatus (2009).

[2] Sawaguchi N, Nishibori M, Tajima K, Shin W, Izu N, Murayama N and Matsubara I. Electrochemistry 74 (2006) 315-320.

[3] IEC 61779-1 Electrical apparatus for the detection and measurement of flammable gases – Part 1: General requirements and test methods.

[4] Salyk O, Castello P, Harskamp F. Meas Sci Technol 17 (2006) 3033–41.

[5] Boon-Brett L, Bousek J, Castello P, Salyk O, Harskamp F, Aldea L, Tinaut F. Int J Hydrogen Energy 33 (2008) 7648-7657.

[6] Boon-Brett L, Bousek J, Moretto P. Int J Hydrogen Energy 34 (2009) 562-571.

# $H_2$ Ignition by Hot Surfaces: Safety Issues and Test Methods

**C. Morreale**, **S. Marengo**, **G. Migliavacca**, **A. Maggioni**, Stazione Sperimentale per i Combustibili, Viale A. De Gasperi, 3 - 20097 San Donato Milanese, Italy

## 1 Introduction

Many safety problems associated with the expected diffusion of $H_2$ energy applications have been addressed in research studies and relevant standards.

However, some specific safety aspects or properties remain somehow undefined; one such subject is the ignition of hydrogen-air mixtures by thermal sources. Due to the lack of reliable experimental data, safety rules contained in various technical sheets and standards assume the auto-ignition temperature as a reference. This parameter, though, is quite uncertain itself, as demonstrated by the wide range reported in the literature (1). Moreover, heating the whole gas mixture up to the limit temperature leads to conditions which are far from the most likely scenario of ignition subsequent to an accidental release.

Data on ignition of flammable gas mixtures near ambient temperature by hot sources can also be found in the literature (2-5), but the temperature is obtained by various methods involving undefined uncertainty of the measurement. In addition, the non-uniformity of surface temperature is recognized also for small surfaces. The experimental difficulty in measuring the actual temperature is a major cause of the dispersion of available data on this subject; in fact the range of reported ignition temperature of $H_2$/air is from 640 to 930 °C (3).

Additional problems are posed by the possible partial consumption of the reactants, with formation of a strong inhibitor as water vapor, during stabilization of the reaction systems, and by the modification of the heating element (strip, rod or filament).

Actually, there are very good reasons to refine the methods for the determination of ignition temperature of hydrogen on hot surfaces. In fact, an underestimation of the possible risks can have obvious dramatic effects related to accidents; on the other hand, the overestimation of this parameter can lead to unsustainable costs associated with safety measures, and in the long range to a negative impact on the general acceptance of hydrogen technologies.

An advanced method for the study hot surface ignition should take in due account these problems, and in the same time assure test conditions which realistically reproduce possible scenarios of hydrogen leakage. The method proposed here tries to address these issues.

## 2 Methods and Results

Previous studies conducted at our Institute on surface reactivity of flammable gas mixtures (6), have suggested that a method for determining the conditions of ignition on hot materials should exhibit the following characteristics:

- Provide an accurate and reliable measurement of the surface temperature under test conditions

- Adopt an experimental set-up which reproduces the most likely conditions of accidental $H_2$ release leading to ignition
- Utilize state-of the art techniques and instruments, and in the same time be simple enough to be easily implemented in the bench scale

A key aspect of these measurements is the controlled heating of the potential ignition source. Since the known region of ignition temperature for $H_2$/air mixtures is relatively high, resistive heating is suitable for metallic materials. In this case a contact method is not recommended for temperature measurement, and infrared imaging with high spatial resolution represents the best option. Imaging of the ignition source also allows a direct control of the history of the sample throughout the test, revealing any physical change (such as deformation or even rupture of the wire or plate) capable of affecting the results. In this experimental study we utilized a FLIR Thermovision SC 4000 camera, operating in the spectral range between 1.5 and 5 micron.

In the proposed method, the test is conducted in dynamic conditions, with the flammable mixture flowing over a metal sheet or wire placed in a sapphire tubular reactor. This relatively expensive material was chosen for the excellent mechanical and optical properties; however a quartz reactor gave also a good performance. For experiments above atmospheric pressure, a proper reaction chamber equipped with a sapphire or quartz window can be used.

The control of the gas flow rate and composition is obtained by electronic mass flow meters and by on line analysis with a Varian CP-4900 micro gas chromatograph equipped with advanced TCD detectors and two capillary columns. The system provides capability of determining the concentration of permanent gases and volatile compounds in 60 to 90 seconds, with relatively high sensitivity (below 100 ppm).

Fig. 1 shows a high-resolution thermal image of a thin steel plate placed in the reactor and resistively heated. Temperature in each point of the surface can be measured, recorded and processed in real time, allowing an accurate evaluation of the real temperature conditions to which the flowing $H_2$/air mixture is exposed.

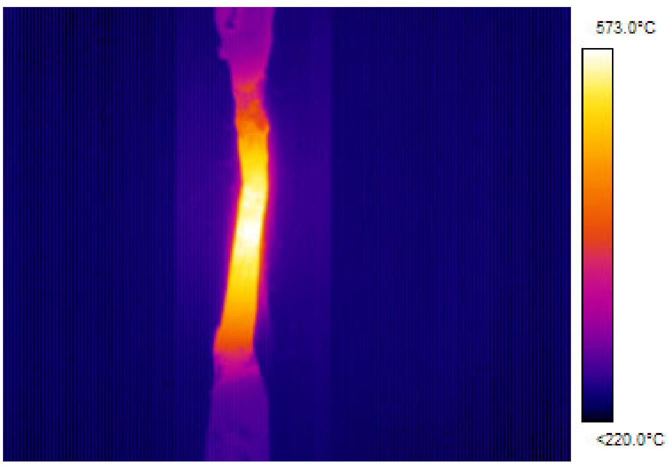



**Figure 1: Thermal infrared image of a steel sheet during an ignition test.**

In this way we obtain the plot shown in Fig. 2, where the maximum temperature of the metal surface is recorded as a function of time.

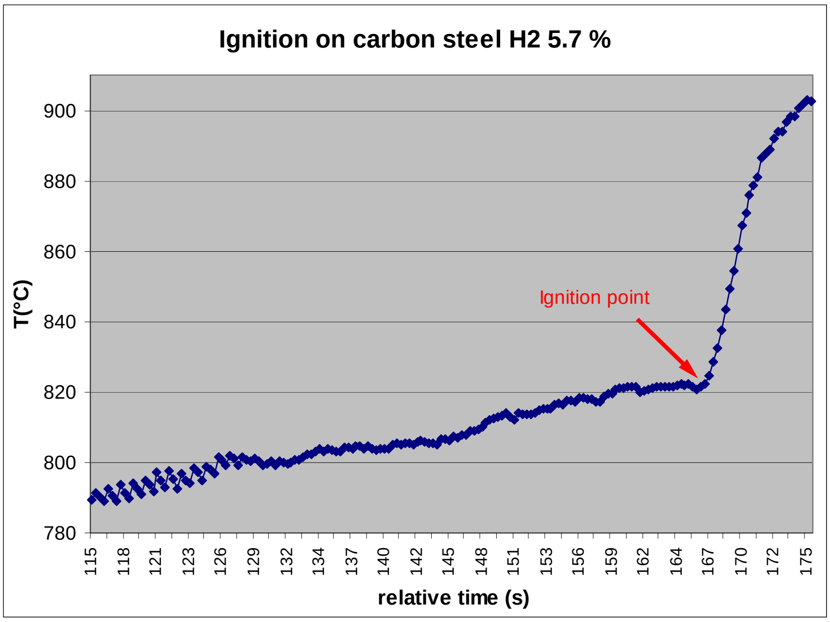



**Figure 2: Evolution of surface temperature in the proximity of $H_2$/air ignition.**

The high temporal resolution of the thermal imager allows the exact detection of the ignition onset (marked with the arrow) and of the corresponding surface temperature.

Table 1 shows some significant results obtained with lean $H_2$-air mixtures contacted with the hot metal surface. The role of different parameters is clearly evidenced from these data. The sheet of carbon steel provokes ignition of the 5.7 % mixture at 820 °C. A slight increase in hydrogen content lowers the ignition temperature to 760 °C; a higher residence time of the gaseous mixture produces a further decrease in the ignition temperature.

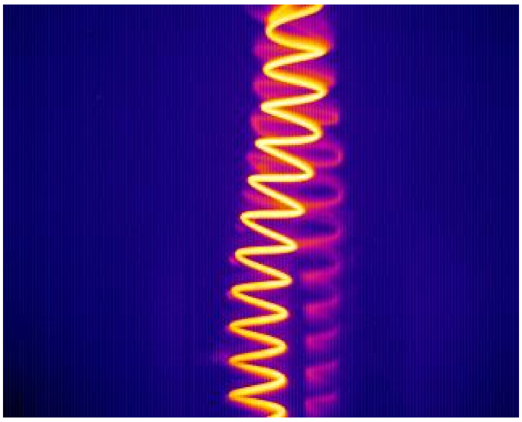
**Table 1: Ignition temperature of $H_2$/air mixtures on hot metal surfaces.**

| Metal surface | $H_2$ concentration (%) | Gas flow rate (ml/min) | Ignition Temperature (°C) |
|---|---|---|---|
| Carbon steel* | 5.7 | 100 | 820 |
| Carbon steel* | 6.5 | 100 | 760 |
| Carbon steel* | 6.5 | 50 | 720 |

* exposed to corrosive environment

The metal sheet utilized in these tests had relatively large section: 4x0.4 mm, which required dissipation of significant electric power to reach and maintain high temperatures.

For a more detailed study of the hot surface effects, the sheet was replaced by a thin metal coil or wire, which required quite smaller electrical power. In this way, a simpler and stable electric circuit could be utilized to adjust the metal temperature.



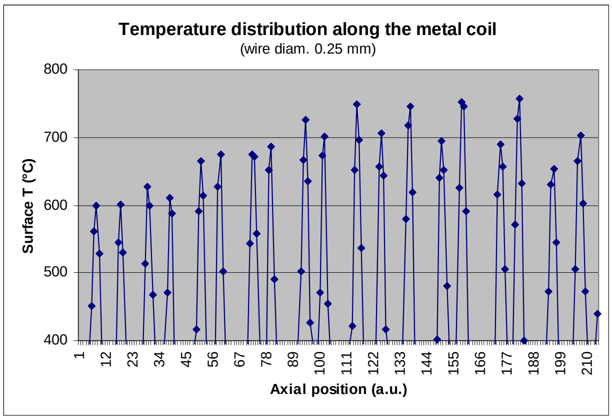



**Figure 3: Thermal IR image and axial temperature profile (red line) of a steel coil.**

Fig. 3 shows an example of the thermal image of a AISI 302 steel coil resistively heated to high temperature. The sample has a diam. of 0.25 mm and a length of 34 mm. It can be seen that the temperature distribution on the surface can be accurately determined by the IR camera, in spite of the small dimensions, as shown by the axial profile corresponding to the red line. A reliable value of the maximum surface temperature can thus be obtained. Some preliminary results obtained by passing an $H_2$/air mixture over the heated wire with a residence time of 7 seconds are reported in Fig. 4.

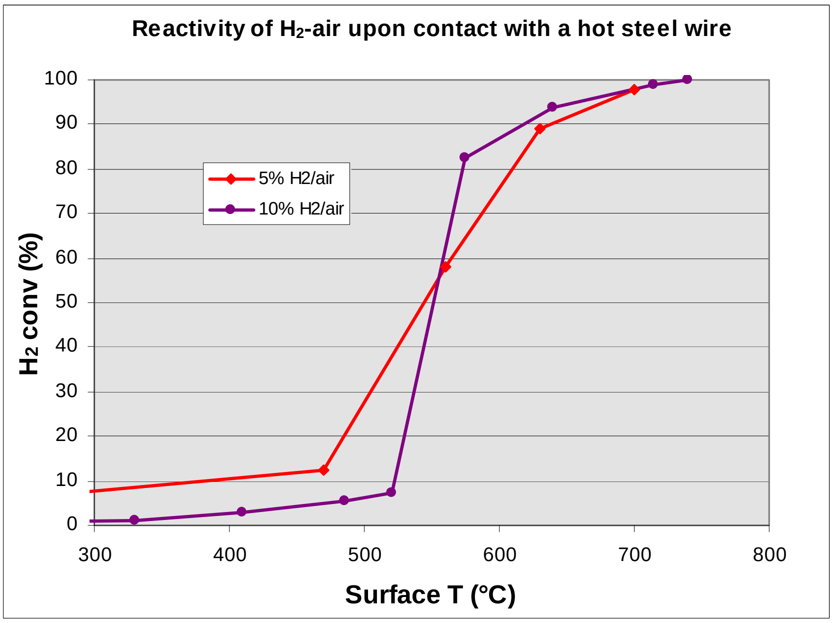



**Figure 4: $H_2$ consumption upon exposure to a hot metal wire.**

Between 480 and 600 °C, a dramatic increase in $H_2$ conversion was measured at the reactor outlet. The behavior is similar for the two different $H_2$ concentrations examined. This conversion can be attributed to surface reactions occurring on the small surface of the metal as well as to gas phase reactions taking place in a heated zone close to the wire. It is important to notice that ignition of the gas mixture did not take place. For very lean mixtures, the hot wire is unable to trigger the propagation of the oxidation throughout the gas. This is in accordance with literature data, showing the marked influence of the size of the hot surface on ignition (4).

However, even in the absence of ignition, it is possible to estimate a temperature range where a high reaction rate is established, with subsequent significant heat release, thus determining the conditions for ignition. From the examination of the temperature/conversion data, we can deduce that around 620 °C a contact time of about 7 sec is needed to achieve an $H_2$ conversion of 90 %. Above 700 °C conversion is complete. It can be deduced that below that temperature a sudden ignition of a lean $H_2$/air mixture is unlikely. This result is in line with the lowest ignition temperatures reported in the literature (3).

## 3 Conclusions

Experimental techniques and criteria for estimating the temperature of hot surface ignition have been proposed. The major features of the method are a fine control of fluodynamic conditions, efficient gas analysis, and accurate temperature measurements by real-time thermal imaging of the surface representing the potential ignition source.

The ignition phenomenon can be investigated in good detail using resistively heated metal sheets exposed to a flammable mixture under controlled environment. However, electric power generation and dissipation have to be properly managed.

By scaling down the testing system to thin filaments, a more versatile procedure can be defined, which provides detailed information on the kinetics of $H_2$ oxidation.

These experimental methods can be applied to different metallic materials representing potentials ignition sources and to richer hydrogen mixtures, in order to create a comprehensive database to be utilized in a wide range of risk analysis scenarios.

## References

[1] Basic considerations for the safety of hydrogen systems, ISO/TR 15916 (2004).

[2] B. Lewis and G. von Elbe, Combustion, Flames and Explosions of gases, 3rd ed., Academic Press, New York (1987) pp. 361-380.

[3] J.W. Buckel and S. Chandra, Hot wire ignition of hydrogen-oxygen mixtures, Int. J. Hydrogen Energy 21 (1996) 39-44.

[4] N.M. Laurendau, Thermal ignition of methane-air mixtures by hot surfaces:a critical examination, Combustion and Flame 46 (1982) 29-49.

[5] R.K. Kumar, Ignition of hydrogen-oxygen-diluent mixtures adjacient to a hot, nonreactive surface, Combustion and Flame 75 (1989) 197-215.

[6] S. Marengo, G. Migliavacca, F. Hugony, A. Maggioni and C. Morreale, Reactivity of $H_2$/air Mixtures Over Hot Metal Surfaces, in Proc. Hypothesis VIII, C.M. Rangel, G. Spazzafumo Eds, Lisbon, 1-3 april 2009.

# SM Existing and Emerging Markets


SM.1 Off-Grid Power Supply and Premium Power Generation

SM.2 Space and Aeronautic Applications

SM.3 APUs for Road Vehicles, Ships and Airplanes

SM.4 Portable Applications and Light Traction

# Sizing of Photovoltaic System Coupled with Hydrogen Storage Based on the ORIENTE Model

**Christophe Thibault, Christophe Darras, Marc Muselli, Philippe Poggi**, University of Corsica, France

The future belongs to renewable energy sources, and satisfying the energy growing demand for sustainable energy sources must be one of the highest priority for research in the energy field. The systems based on these sources have a limited ecologic impact because they only use hydrogen and solar energy. The solutions based on renewable energy are very promising when it comes to supply energy to isolated sites, with problems related to their location. Concerning hydrogen-based solutions, the objectives are not only to improve the performances of hydrogen production and storage solutions, but also to associate them effectively with renewable energy sources [1, 2].

PEPITE (study and experimentation of intermittent energy management using electrochemical technologies) is a project endorsed by the French PAN-H research program (action plan on hydrogen and fuel cell) supported by ANR (French Research National Agency). This project started in January 2008 for three-year duration. The aim of the project is to evaluate different system architectures and energy management strategies for hybrid systems based on renewable energy sources coupled with hydrogen for different applications. The system is composed of a PV array, an electrolyzer (PEM), a fuel cell (PEM), batteries, gas and water storage solutions, and also an electrical architecture to couple the whole system and the load. Finally the interest of this project is to propose and to evaluate solutions for isolated sites or for grid-connected applications supplied by PV/FC/El system [3, 4]. In this project, the sizing of each sub-system has to guarantee an optimal system efficiency [5-12]. An exclusive sizing tool based on a numerical optimizing code named ORIENTE (Optimization of Renewable Intermittent Energies with Hydrogen for Autonomous Electrification) was developed under Matlab$^{TM}$ software [13], and assumes sequentially running time. A weather station located in Cadarache (CEA, France) will represent the load which will be supplied b the designed PV/FC/El hybrid system for the demonstration. In our case, the demonstration system (fig.1) will be composed by a PV array, a PEM fuel cell and PEM electrolyzer with their auxiliaries, batteries, and storage tanks for $H_2$, $O_2$ and $H_2O$, and associated converters. In this hybrid system, batteries are transparent energetically at normal functioning.

They are also used in normal regime to maintain the potential of the BUS, to assure the start-up/stop in correct conditions and finally to smooth the electrical power from the fuel cell and the electrolyzer system. They have to be in charge before the functioning of the system. In this paper batteries are not used as means of storage (in opposition with other projects or they are considered like a short-term energy storage), but they must be sized regarding smoothing of electrical power. Thus, for our project, hydrogen is used as means of short and long-term storage too.

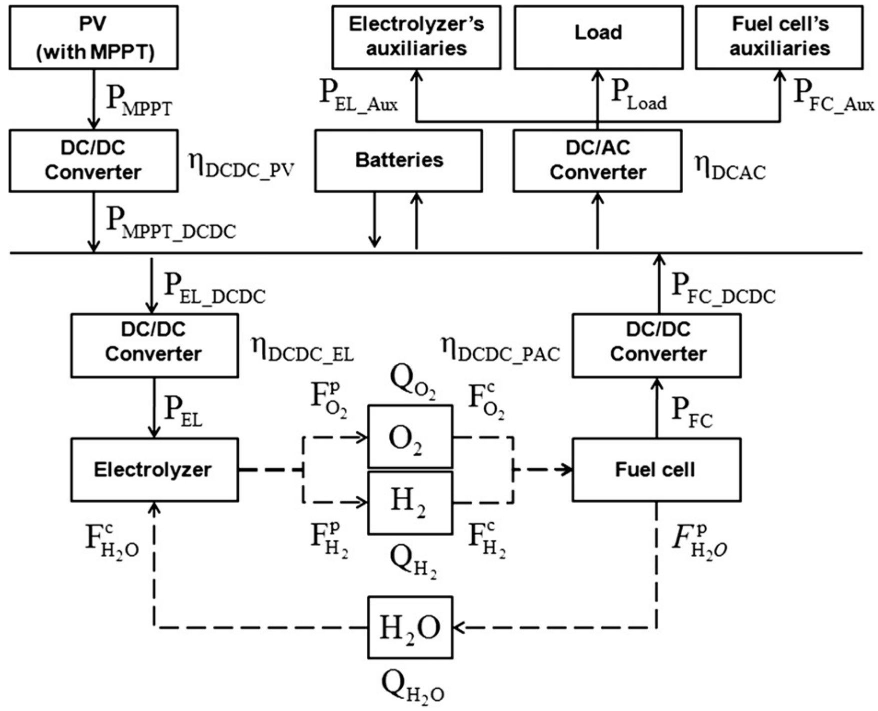



**Figure 1: Representation of the studied PV/$H_2$ hybrid system.**

The load that must be fed by the energy system is represented by a meteorological station (weather pylon) wit the consumption of its control command sub-system, the thermal management of the PV/FC/El system; and the gas storage's auxiliaries, corresponding to 6500W of constant power operating 24/24 hours. The global hourly solar radiation (45° tilted) and ambient temperature data were measured (local time), a few meters away from the weather station of Cadarache (France). The data are available from the 1st July 2002 to the 30 June 2003 (8760 hours). From the data, monthly means of hourly values are represented (Fig.2) only computed on sunshine periods.

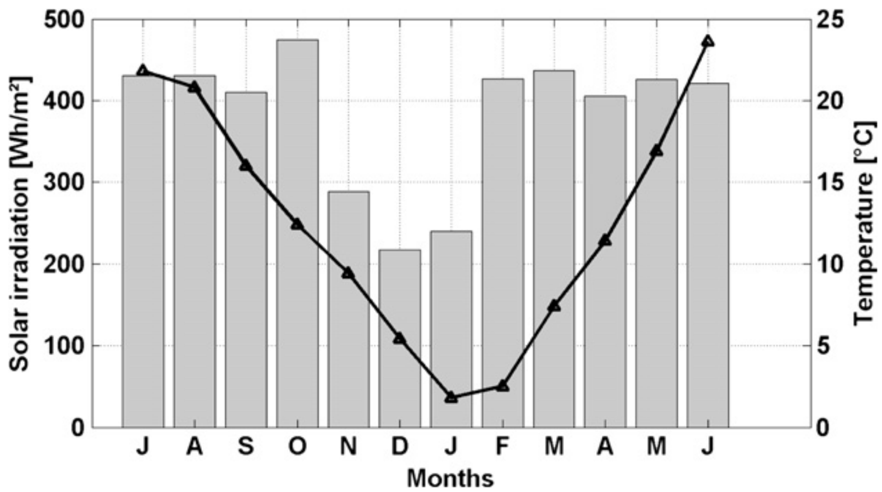



**Figure 2: Meteorological data monthly mean.**

The Fig. 3 describes the proposed flow control. The PV array supplies in priority the load *via* the DC/AC converter. In the case of an excess of PV power (above the power threshold of the electrolyzer) and a non-full hydrogen storage, this extra power will be transferred to the electrolyzer *via* its DC/DC converter. If the electrolyzer cannot absorb it (under the power threshold or full storage) then the “transparent” batteries could absorb it to a certain limit depending of their sizing. And if the batteries are full, then the PV array is totally shut down. When the PV array is not able to satisfy the load power, the fuel cell supplies the complementary amount of power. If the power required for the fuel cell is under its power threshold or if the gas storage is empty, the “transparent” batteries could supply it to a certain limit depending of their sizing. And if the batteries are fully discharged, then the system is shut-down. The last case should not happen because we size exactly the system to avoid this scenario. Nevertheless it is necessary for the electric safety of the system.

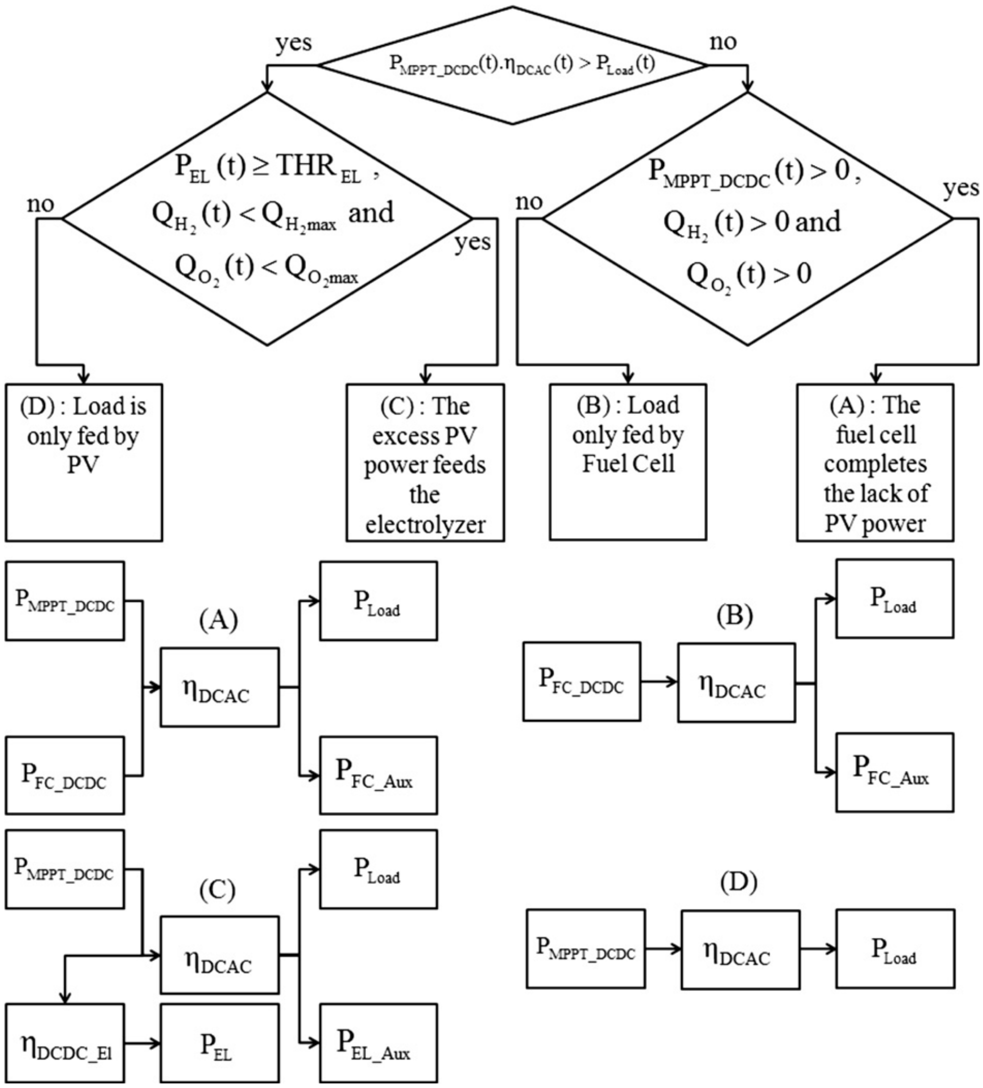



**Figure 3: Proposed flow control.**

For an optimization of the system components, ORIENTE uses the hourly weather data (solar radiation and ambient temperature) and the hourly load profile. The internal parameters of each sub-system are already in the model, with the possibility to modify them. The optimization follows this way:

1. We define minimum and maximum PV powers, with corresponding to numbers of modules.
2. DC/DC converter associated to PV array is sized according to the maximum power that able to deliver (according to the number of modules)
3. Fuel Cell is sized according to the maximum power that the load can need, by considering efficiencies of the converter associated to the FC, the DC/AC converter, and the auxiliaries' consumption. By using the active area of an elementary fuel cell and the operation potential on V-I curve. The optimized parameter is the number of elementary cells in series. It gives us the FC power to be installed. The DC/DC converter associated to the FC and the DC/AC converter are sized according to the maximum power to be delivered.
4. The electrolyzer is sized according to the maximum excess power that the PV can produce, by considering the efficiencies of the converter associated to the electrolyzer, the DC/AC converter, and the auxiliaries' consumption. By using active area of an elementary electrolyzer cell and the operation current on V-I curve (maximal potential on the curve which we wish that the electrolyzer can work). The optimized parameter is the number of elementary electrolyzer power to be installed. The DC/DC converter associated to the electrolyzer is sized at the same time according to the maximum power to be absorbed.

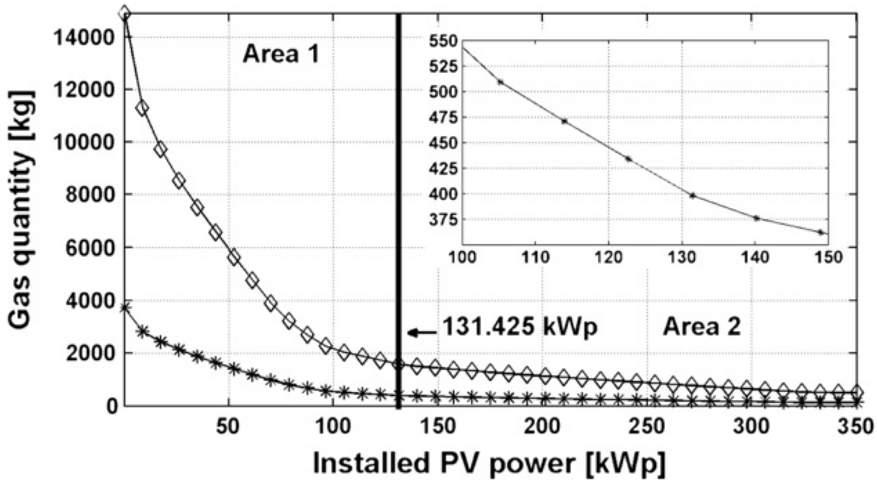



**Figure 4: Optimization sizing curve (1 year period).**

Fig. 4 represents the optimization curves of the PV/FC/El system. The higher the installed $P_{PV}$ power is, the lower the size of the gas storage tank for the required autonomy (the range of the hydrogen amount is between 3725 Kg and 398 Kg for an installed PV power respectively equal to 0 and to 131.425 kW, and 398 Kg to 125 Kg for a PV power between 131.425 and 350.175 kW). This figure can be divided into two parts. The limit is the point where the PV power is such as the system consumes and produces the same amount (fig.5). When $P_{PV}$=131.425 kWp, about 2050 kg of $H_2$ are both produced and consumed. In the first area, the system is unsustainable. Operating a second year with the same sizing and the same load and the same meteorological profile would require a gas refueling to be sustainable. Beyond the line (area 2), the system is sustainable and the gas storage would never be empty.

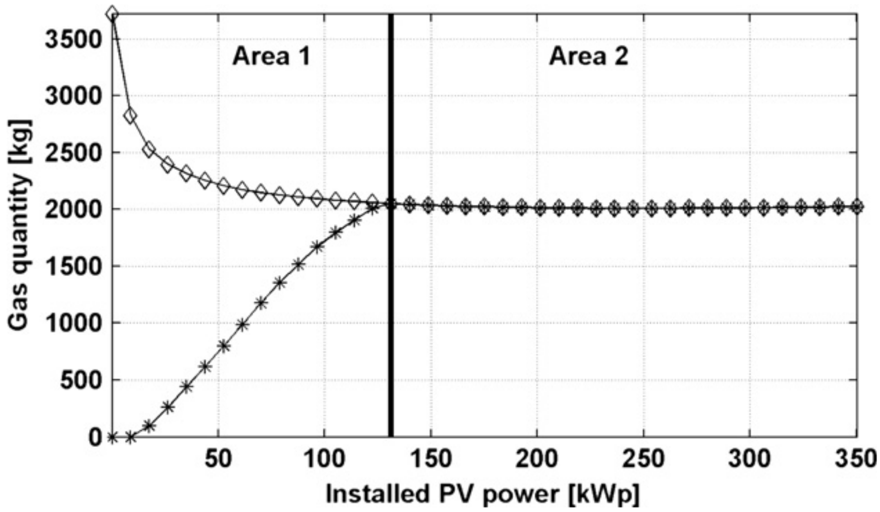



**Figure 5: $H_2$ consumption (- ◊ -) and production (- * -) curves in kg (1 year period).**

In conclusion we showed that we are able to determine a “sustainable” point for such a system in terms of sizing. Moreover ORIENTE makes it possible to describe in details the energy exchanges within such a complex system. A 24/24 hours system needs huge components, so an economic study will be necessary in order to know if the system cost and if such a configuration are economically acceptable. This study is currently continuing to evaluate the economic part and the interest of a hydrogen chain at this power level compared with storage *via* batteries alone.

## References

[1] Zini G, Tartarini P. Hybrid systems for solar hydrogen: A selection of case-studies. Applied Thermal Engineering 29(2009) 2585-2595

[2] Yilanci A, Dincer I, Ozturk H.K, A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications. Progress in Energy and Combustion Science 35 (2009) 231-244

[3] Paramashivan Kaundinya D, Balachandra P, Ravindranath N.H. Grid-connected versus stand-alone energy systems for decentralized power – A review of literature. Renewable and Sustainable Energy Reviews 13 (2009) 2041-2050.

[4] Eltawil M. A, Zhao Z. Grid-connected photovoltaic power systems: Technical and potential problems – A review. Renewable and Sustainable Energy Reviews 14 (2010) 112-129.

[5] Kaldellis J.K, Zafirakis D, Kondili E. Optimum sizing of photovoltaic-energy storage ystems for autonomous small islands. Electrical Power and Energy Systems 32 (2010) 24-36.

[6] Ulleberg O, Nakken T, Eté A. The wind/hydrogen demonstration system at Utsira in Norway : Evaluation of system performance using opertational data and updated hydrogen energy system modeling tools. International of Hydrogen Energy 35 (2010) 1841-1852.

[7] Hwang J.J, Lai L.K, Wu W, Chang W.R. Dynamic modeling of a photovoltaic hydrogen fuel cell hybrid system. International Journal of Hydrogen Energy 34 (2009) 9531-9542

[8] Dufo-Lopez R, Bernal-Augustin J.L. Design and control strategies of PV-Diesel systems using genetic algorithm. Solar Energy 79 (2005) 33-46

[9] Dufo-Lopez R, Bernal-Augustin J.L. Multi-objective desing of PV-wind-hydrogen-battery systems. Renewable Energy 33 (2008) 2559-2572

[10] Uzunoglu M, Onar O.C, Alam M.S. Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. Renewable Energy 34 (2009) 509-520

[11] Shahnia F, Majumder R, Ghosh A, Ledwich G, Zare F. Operation and control of a hybrid microgrid containing unbalanced and nonlinear loads. Electric Power System Research (2010) (in press)

[12] Zini G, Marazzi R, Pedrazzi S, Tartarini P. A solar hydrogen hybrid system with activated carbon storage. International Journal of Hydrogen Energy (2009) 1-9 (in press)

[13] Darras C, Sailler S, Thibault C, Muselli M, Poggi P, Hoguet J.C, Melscoet S, Pinton E, Grehant S, Gailly F, Turpin C, Astier S, Fontès G. Sizing of photovoltaic system coupled with hydrogen/oxygen storage based on the ORIENTE model. International Journal of Hydrogen Energy (2010) 1-11 (in press)

# Tool for Optimal Design and Operation of Hydrogen Storage Based Autonomous Energy Systems

**B. Oberschachtsiek, D. Lemken**, ZBT- Duisburg, Germany
**M. Stark, G. Krost**, University Duisburg-Essen, Germany

**Abstract**

Decentralized small scale electricity generation based on renewable energy sources usually necessitates decoupling of volatile power generation and consumption by means of energy storage. Hydrogen has proven as an eligible storage medium for mid- and long-term range, which – when indicated – can be reasonably complemented by accumulator short term storage. The selection of appropriate system components – sources, storage devices and the appertaining peripherals – is a demanding task which affords a high degree of freedom but, on the other hand, has to account for various operational dependencies and restrictions of system components, as well as for conduct of load and generation.

An innovative tool facilitates the configuration and dimensioning of renewable energy based power supply systems with hydrogen storage paths, and allows for applying appropriate operation strategies. This tool accounts for the characteristics and performances of relevant power sources, loads, and types of energy storage, and also regards safety rules the energy system has to comply with. In particular, the tool is addressing small, detached and autonomous supply systems.

## 1 Introduction

Small autonomous energy supply systems based on renewables such as solar and wind power can significantly contribute for saving fossil energy resources as well as for $CO_2$ emission reduction; on the other hand, heavy fluctuations caused by solar day/night cycles and/or weather dependent irradiation as well as wind volatility complicate proper and continuous operation. According to the particular load demand, this implies the necessity to provide short and/or long term energy storage. The selection of appropriate storage types and sizes finally depends on the renewable energy source chosen, the expected energy harvest profile, as well as load demand characteristics.

Various principal configurations are supposable for autonomous, decentralized and renewables based systems for the electric supply of, for instance,

- remotely located telecommunication base stations (up to 2.5 kW) [1], [2];
- solitary buildings such as alpine huts, summer residences or small farms (up to 5 kW) [3], [4];
- farms and small settlements in developing countries (above 5 kW) [5].

To assure effectiveness in practical operation, appropriate selection and dimensioning of the particular components is indispensable. This requires collection of comprehensive knowledge and experience from various domains such as electrical, process and chemical engineering, and is therefore a complex and time consuming task.

A tool being able to prudently and flexibly master this task is currently under development and will be presented in the following; such tool must rely on the knowledge of above mentioned domains, comprising the characteristics and specifics of available system components, their applicable variants (e.g., pressurized vs. metal-hydride hydrogen storage), and must consider the operational interactions and restrictions between all system components involved. The tool conducts the system design in the following steps:

1. constitution of system architecture under energetic and economic aspects;
2. dimensioning of components by operative simulation of the complete system;
3. development of an appropriate operation strategy for the complete system.

An expert system was chosen for task a) of components selection as it provides transparent and clearly arranged set-up of rules, weighting of input information and inferences, as well as an explanation capability; it is described in more detail in [6].

Task b) demands simulation of the entire plant under consideration of realistic load and (renewables based) generation profiles for longer periods of time with at the same time sufficient temporal resolution in order to comply with daily load and generation fluctuations; an appropriate simulation package comprising models of various plant components was presented in [7]; several of these models are applied here, too. Rather, the operational behavior of metal hydride storage embedded within a hydrogen path has yet to be modeled according to the results of measurements as briefly sketched below in section 5 and more extendedly described in [8].

Finally, an equitable operation strategy c) is required which cares for reliable, un-interrupted supply under smooth commitment of devices in order to maximize their lifetime expectancy and minimize operation cost.

This design tool will be sketched in the following; the functional part a) was finalized most recently while parts b) and c) are under present development. After completion the tool will be a significant contribution to the launch of small hydrogen storage based energy systems.

## 2 Power Supply Structure

The main components, which self-sustaining renewable energy based electricity supply systems typically consist of, can be seen in Fig. 1. Types of renewable energy sources (solar/wind) usually are disposed according to local conditions (given irradiation/wind profiles, space for allocation etc.), as well as given load shapes/cycles. Small wind generators are available on the market, and photovoltaic (PV) panels can be individually composed to arbitrary peak power output.

Coincidence of sources and load profiles further determines existence and intent of storage types, used in particular for short term (day/night cycles) and/or mid-/long-term (weather periods, seasons) time range. While accumulators (conventionally usually lead-acid or NiMH but increasingly lithium-ion types) are well suited for short term storage, hydrogen has proven well as a reasonable mid-/long-term storage medium in consequence of low storage losses [9], [10].

For hydrogen production electrolyzers [11] with appropriate ratings are available; in case of pressurized hydrogen gas storage, high pressure electrolyzer types save separate compression effort. On the other hand, as another promising technology metal-hydride beds provide easy and safe hydrogen storage. Such metal-hydride storages allow a higher energy density than pressurized gas storages, which reduces the required space, and provide intrinsic safety by “freezing” in case of leakage [12], [13].

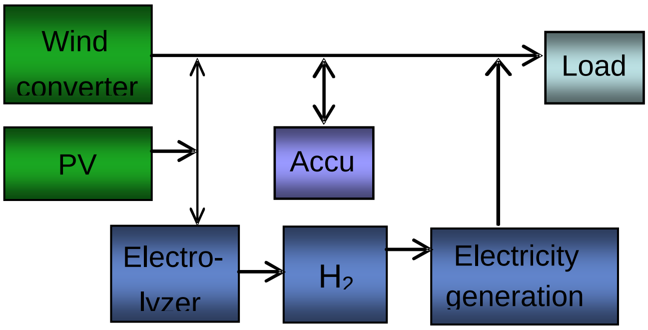



**Figure 1: Self-sufficient electrical power supply structure.**

The re-conversion of hydrogen to electricity can be achieved by either small gas-engine driven generators, or fuel cells [14], which both are available in relevant ratings. In general, but especially in the latter case, cost considerations play a weighty role if commercial and not pilot systems are considered. Table 1 taken from [2] gives an exemplary survey of various self-sustaining telecommunication base supply systems with typical loads ranging from some tens of W up to 2.3 kW.

**Table 1: Self-sustaining renewable energy based telecommunication hub supply approaches [2].**

| Application | Site power required | Example solar and wind solution |
|---|---|---|
| GSM Base Station 2/2/2 | 600 - 1800 W | 4 kW Solar Array and 6 kW turbine depending upon conditions |
| GSM Base Station 4/4/4 | 900 - 2300 W | 6 kW Solar Array and 6 kW turbine depending upon conditions |
| UMTS Node B Macro/Fiber - 2/2/2 | 750 - 1000 W | 3 kW Solar Array and 2.5 kW turbine depending upon conditions |
| UMTS Node B Macro/Fiber - 4/4/4 | 1300 – 1700 W | 4 kW Solar Array and 2.5 kW turbine depending upon conditions |
| Large WiMax Base Station | 1.3 kW (4 Sector) | 4 kW Solar Array and 2.5 kW or 6 kW turbine depending upon conditions |
| Metro WiFi | <30 W includes a back-haul solution | 100 W Solar Array and small turbine depending upon conditions |
| P2P link (two heads) | 110 W for two units | 1 kW Solar Array and 600 W or 2.5 kW turbine depending upon conditions |

## 3 Expert System Based Components Selection

An expert system was chosen for the task of components selection, because it provides clearly arranged knowledge input in form of rules, weighting of choice factors, as well as transparency in reasoning by an explanation subsystem. The multitude of implemented rules (581 in total) results from the detail grade of parameters considered, such as:

- Local generation conditions:
  - *expected yearly wind/solar energy harvest*: the particular source is only favored if certain site-specific parameters exceed a given threshold value (e.g. 900 kWh/a per $m^2$ for solar irradiation or 3 m/s average wind speed); special aspects such as shadowing of photovoltaic modules or slipstream of wind turbines are also regarded;
  - *available area*: the particular source is only considered if the available plant area (for, e.g., photovoltaic modules surface) admits harvest of global yearly energy demand;
  - *quality of solar radiation:* diffuse or direct radiation require different types of photovoltaic panels (amorphous vs. mono-crystalline);
  - *installation circumstances:* selection of system components depending on building restrictions such as height of plant, etc.
- Qualitative load conditions:
  - *cyclicity of load profile*: co-incidence/adversity of load forecast and energy harvest expectation (e.g., load peaks during daytime give favor for photovoltaic approach);
  - *volatility* of load: heavy and rapid discrepancies between load maxima and minima substantiate the necessity of short term storage.
- Storage conditions:
  - *hydrogen path*: needed for compensation of solar seasons-based cyclicity (long term) [15], or for bridging calm wind periods (mid-term);
  - *accumulator*: required for solar day-night cycle and/or fast power peak compensation (short term).
- Storage technology:
  - *hydrogen path*: metal hydride vs. pressurized gas,
  - *accumulator*: lead-acid, lithium-ion or NiMH,
  - according to, e.g., economical and innovation aspects. For hydrogen storage, the type of electrolyzer is selected under consideration of the $H_2$ pressure required by the actual storage technology.
- Electricity generation from hydrogen:
  - the *relevant component* (gas engine driven generator, fuel cell) is determined under global consideration of the existing load conditions.
- Component specific conditions:
  - *operative restrictions* such as minimal operation time, minimal/maximal loading of certain devices etc.;

   - *safety rules* demanding restrictions in use of hydrogen.
- Economic considerations:
   - enlargement of basal physical expert system rules by *economic aspects* (e.g., less expensive amorphous photovoltaic cells if module surface area admits).
- Innovation considerations:
   - possible release for choosing *innovative system components* if available; in this case, costs are of second range.
- Comparison with preliminary selection by operator:
   - a *preferred set of components* selected by the user in advance can be regarded and compared to the expert solution by hindsight.

The implementation was made by use of the freely available shell “KnowMe” [16]. The expert system was tested with multiple autonomous power supply requirements ranging from simple telecommunication bases up to rural settlements in extreme climatic zones. In all cases the suggestions have proven as plausible and useful; several examples are given in [6]. In Fig. 2 an example of the explanation surface is given, reasoning the application of a certain rule and weighting.


**Figure 2: Explanation functionality displaying the corresponding rule(s) and weighting(s).**

## 4 Dimensioning of Components and Regard of Operative Conditions

After selection of components their sound rating is the logical next step. The realized concept provides a library of individual modular component blocks based on Matlab/Simulink® models of

- stochastically operated primary sources (photovoltaic and wind generation, both of different types),
- electrolyzers of different types (including high pressure electrolyzers),
- long and short term storage systems (e.g. variants of hydrogen storage, various accumulator types),
- conversion of stored hydrogen to electricity (fuel cells and small gas engine driven gen-sets)

from which the particular complete energy systems can be individually composed according to the results of the components selection. For proper dimensioning, operation of the complete plant with given load and wind/solar generation profiles has to be simulated and optimized over longer periods of time – usually a complete year for rating of seasonal storage – at sufficient temporal resolution (typically 15 min) in order to widely cover power peaks and short term storage requirements. This part is presently under development and will largely be relying on component models which were successfully applied for multi-criterial optimization of micro CHP home plant operation [17]. The task considered here is of minor complexity, nevertheless the operational restrictions such as minimal run time of components or maximal number of operation cycles per day etcetera have also to be considered; the optimization process itself which can be arbitrarily oriented to technical, energetic or economic aspects is comprehensively described in [18].

## 5 Measurements as Basis of Metal Hydride Storage Modeling

In particular, for hydrogen storage different principles are applicable: liquid (of less importance for the demands considered here), pressurized gas or metal hydride. Especially for the latter relevant data for exact modeling are not yet available. Therefore, comprehensive and systematic measurements are currently conducted, the results of which will complement the corresponding simulation model.

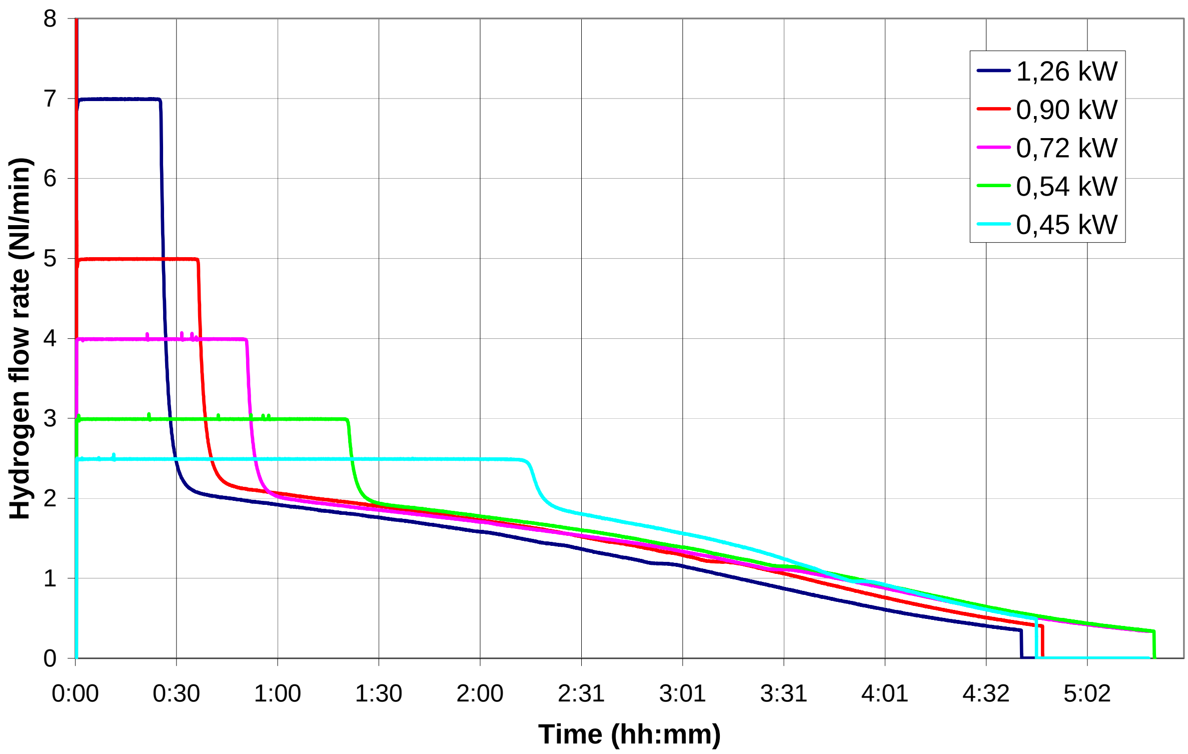



**Figure 3: Desorption curves for different hydrogen flow rates at ambient temperature of 25 °C.**

Two very similar metal hydride storage tanks, which are designed for a reversible hydrogen capacity of about 60 g, have been tested so far. Typical desorption curves of such a tank are shown in Fig. 3. Different set points of the hydrogen flow rate were adjusted at an ambient temperature of 25 °C. The maximum duration of constant flow rates varies from less than 30 minutes for an adjusted flow rate of 7 Nl/min to more than 2 hours for 2.5 Nl/min. It can be seen that by using only one tank a constant hydrogen flow of 5 Nl/min (equivalent to 0.9 $kW_{th}$) can be provided for about 37 minutes. With two tanks operated in parallel the constant delivery time can not only be doubled but be expanded by a factor of 3.6 up to 134 min. Another important influencing factor on the duration of a required hydrogen flow is the ambient temperature of the tested tank. As seen in Fig. 4a, the duration of constant hydrogen flow of 5 Nl/min increases nearly one minute per one Kelvin of higher temperature for the tested tanks. Especially in self-sufficient energy systems, where hydrogen storages will not always be filled to maximum, the fill level of the tank has to be considered. As shown in Fig. 4b the lower the fill level is when starting the desorption, the shorter is the operation time for a constant flow (here 5 Nl/min).

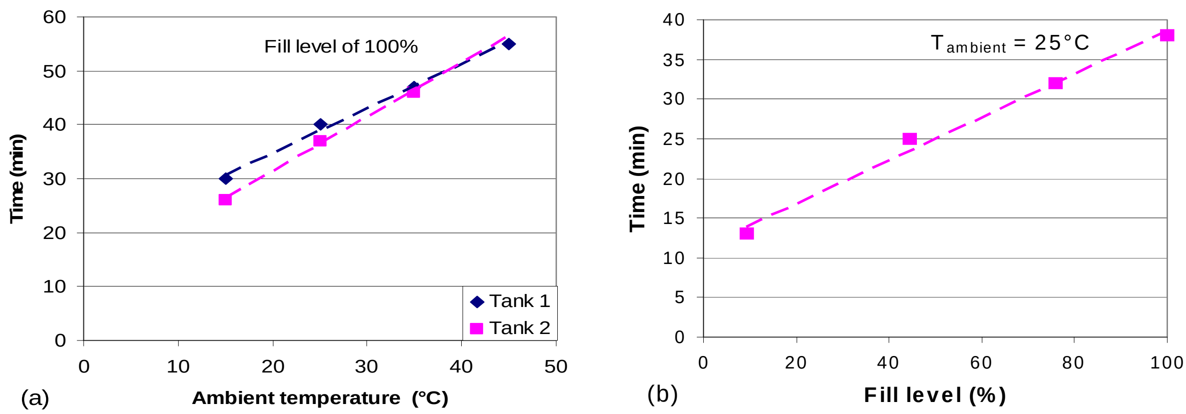



**Figure 4: Influence of ambient temperature (a) and fill level of tank (b) on duration of constant flow rate of 5 Nl/min.**

The next steps will be to obtain relevant data for the charging process such as filling duration and fill level as function of pressure, hydrogen flow rate and temperature. Additionally dynamic test cycles will be performed. The metal hydride storage will be alternately filled and discharged within different time periods from several minutes to hours resulting in different fill levels. So limits of minimum/maximum duration for loading and unloading will be determined. Finally the electrolyzer, metal hydride storage tanks and the fuel cell system will be operated together. At this an investigation of the interaction of the system components is enabled as well as the optimization of operation parameters. Thus, the verification of the simulation of the hydrogen storage path can be performed.

## 6 Conclusion and Outlook

Self-sustained, detached and renewables based electricity supply implicitly requires storage of energy. Even if such systems usually are small with regard to installed power, the multitude of applicable components as well as of constructive, operative, and safety related constraints provokes eligibility of technical assistance in plant design. A comprehensive tool for proper composition, dimensioning and operation of autarkic electricity supply is under development and was briefly sketched. The complete three-step tool will result in

- helping manufacturers of electrolyzers, hydrogen storages and fuel cells to develop concerted building blocks of particular devices which can individually and easily be combined to complete energy systems;
- facilitating the design of self-sustaining energy systems with reasonable operational performance;
- contributing to the development of new application areas of renewable energies;
- supporting the launch of fuel cell technology by easing engineering of the hydrogen path at reduced cost.

## Acknowledgement

Thanks to “Verein für Energie und Umwelttechnik e.V.“ for sponsoring this project (15863 N) with allocated funds from “Bundesministerium für Wirtschaft und Technologie (BMWi)“ through „Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto-von-Guericke" e.V. (AiF)“.

## References

[1] N.N., Sustainable energy use in mobile communication, Ericsson AB, 2007.

[2] N.N., Solutions Paper: Alternative power for mobile telephony base solutions, Motorola Inc., 2007.

[3] P. Hollmuller, J. Joubert, B. Lachal, K. Yvon, Evaluation of a 5 $kw_p$ photovoltaic hydrogen production and storage installation for a residential home in Switzerland, Int J Hydrogen Energy 25, 2000.

[4] K. Voss, A. Goetzberger, G. Bopp, A. Haeberle, A. Heinzel, A. Lehmberg, The self-sufficient solar house in Freiburg – results of 3 years of operation, Solar Energy, 58,1996.

[5] S. Busquet, F. Domain, R. Metkemeijer, D. Mayer, Stand alone power system coupling a PV field and a fuel cell description of the selected system and advantages, Proceedings of the PV in Europe conference, Roma, Italy, 2002.

[6] M. Stark, M. Hausmann, G. Krost, Expert System for Component Selection of Decentralized Self-sufficient and Regenerative Electricity Supply Systems, Proc. of “Intelligent Systems Application to Power Systems (ISAP) 2009”, Curitiba (Brazil), November 2009.

[7] J. Matics, G. Krost, Intelligent Design of PV Based Home Supply Using a Versatile Simulation Tool, Proc. of “Intelligent Systems Application to Power Systems (ISAP) 2005”, Arlington, Virginia (USA), November 2005.

[8] D. Lemken, M. Stark, B. Oberschachtsiek, G. Krost, Self-sufficient and Regenerative Electricity Supply Systems with Hydrogen Based Energy Storage, Conference on Control Methodologies and Technology for Energy Efficiency (CMTEE) 2010, Vilamoura (Portugal), 2010.

[9] P.A. Lehman, C.E. Chamberlin, G. Pauletto, M.A. Rocheleau, Operating experience with a photovoltaic-hydrogen energy system, Int J Hydrogen Energy, 22, 1997.

[10] T. Nakken, L.R. Strand, E. Frantzen, R. Rohden, P.O. Eide, The Utsira wind-hydrogen system – operational experience, EWEC, European Wind Energy Conference, 2006.

[11] B. Paul, J. Andrews, Optimal coupling of PV arrays to PEM electrolysers in solar-hydrogen systems for remote area power supply, Int J Hydrogen Energy, 33, 2008.

[12] E.S. Kikkinides, M.C. Georgiadis, A.K. Stubos, On the optimization of hydrogen storage in metal hydride beds, Int J. Hydrogen Energy, 31, 2006.

[13] B.D. MacDonald, A.M. Rowe, Experimental and numerical analysis of dynamic metal hydride hydrogen storage systems, Journal of Power Sources, 174, 2007.

[14] D. Shapiro, J. Duffy, M. Kimble, M. Pien, Solar-powered regenerative PEM electrolyser/ fuel cell system, Solar Energy, 79(5), 2005.

[15] J.P. Vanhanen, P.D. Lund, J.S. Tolonen, Electrolyser-metal hydride-fuel cell system for seasonal energy storage, Int J Hydrogen Energy, 23, 1998.

[16] KnowMe: http://www.d3web.de

[17] J. Matics, G. Krost, S. Freinatis, G. Dubielzig, Adaptive and Flexible Energy Management for Micro Combined Heat and Power Systems, Proc. of IASTED International Conference on “Power and Energy Systems”, Clearwater, Florida (USA), Jan. 2007.

[18] J. Matics, G. Krost, Micro Combined Heat and Power Home Supply: Prospective and Adaptive Management Achieved by Computational Intelligence Techniques, Applied Thermal Engineering 28, 2008, pp. 2055-2061.

# Backup Power Fuel Cell Systems for Telecom Applications

**Rich Romer**, IdaTech LLC, Bend, OR, USA

## 1 Summary

With the rapid expansion of wireless communication systems worldwide, and the increasing socioeconomic benefits of mobile phone technology, the need for dependable and economical backup power is critical. Electric grid loss throughout the year, whether from severe weather, natural disasters, or limited grid capacity, is an on-going challenge for network operators. An alternative to the traditional backup power for telecom sites is the fuel cell. Telecom companies are increasingly choosing fuel cell systems as backup power because they are a clean, reliable, and low maintenance solution compared to batteries and diesel generators.

The type of fuel cell commercially available today and most appropriate for use with telecommunications sites is the PEM (Proton Exchange Membrane) fuel cell. A PEM fuel cell is fueled by hydrogen and produces electricity through an electrochemical reaction. These fuel cells are compact, durable, reliable, quiet, and operate at peak efficiency in a wide range of climates (-40°C to +50°C) and adverse weather conditions.

In addition, they have few moving parts (thus needing minimal maintenance), come in sizes ranging from 250 W to 250 kW, can readily adjust their electronic output to meet shifting power demands and offer a high energy density. Also, fuel cells are fast starting and can begin delivering electricity within seconds of activation.

## 2 What Is PEM?

Proton exchange membrane (PEM) fuel cell systems are proving to be an attractive alternative to traditional and existing solutions such as valve-regulated lead acid (VRLA) batteries and diesel generators.

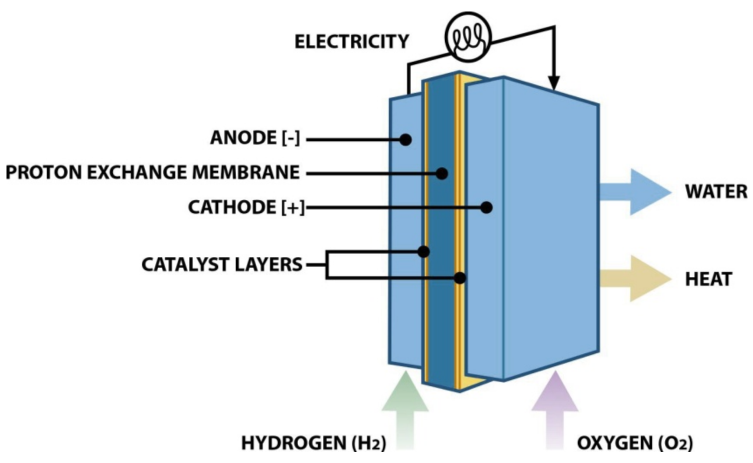



**Figure 1: Proton exchange membrane.**

Membrane electrode assembly consists of anode and cathode, which are each coated on one side with a thin catalyst layer and separated by a proton exchange membrane (PEM). Flow-field plates direct hydrogen to the anode and oxygen (from air) to the cathode. When hydrogen reaches the catalyst layer, it separates into protons (hydrogen ions) and electrons. Free electrons, produced at the anode are conducted in the form of a usable electric current through the external circuit. At the cathode, oxygen from air, electrons from external circuit and protons combine to form water and heat. Individual fuel cells are combined to form a fuel cell stack. Increasing the number of cells in a stack increases the voltage while increasing the surface area of the cells increases the current.

## 3 The Hydrogen Challenge

Typical backup power fuel cell systems use pressurized bottled hydrogen which powers the fuel cell stack and produces regulated DC power and clean exhaust and waste heat. Bottled hydrogen is suitable and cost effective for a range of telecom backup requirements, including eight hours or less of backup power time, lower power needs, and where convenient access to hydrogen refuelling is available. Six bottles of hydrogen provide ten hours of backup power for a 5 kW load. However, in situations requiring extended backup power times, higher power needs or in situations where hydrogen delivery is difficult or impossible, compressed hydrogen is a challenge.


**Figure 3: Compressed hydrogen cylinders.**

The typical run time for one of today's fuel cells operating on 6 cylinders* of hydrogen (*1 T-cylinder = 7,392 liters of hydrogen) is 10 hours at 5 kW of output power. For longer run times, additional cylinders of hydrogen can be hot-swapped into the hydrogen storage cabinet. However, there can be limitations as to how much backup power run time can be achieved by hot swapping cylinders of hydrogen. The run time can be limited by the amount of space for hydrogen storage at a telecom site and/or the remoteness of a telecom site, which makes hot swapping hydrogen cylinders less desirable.

## 4 Liquid Fuel vs. Hydrogen Cylinders

In the comparison between liquid fuel and hydrogen bottles, 55 gallons of HydroPlus, a methanol/water fuel mixture, and a fuel reformer will provide the same amount of power for the same length of time as 30 hydrogen cylinders. In situations where hydrogen storage is difficult due to space and weight restrictions, then HydroPlus liquid fuel combined with a fuel reformer makes sense.

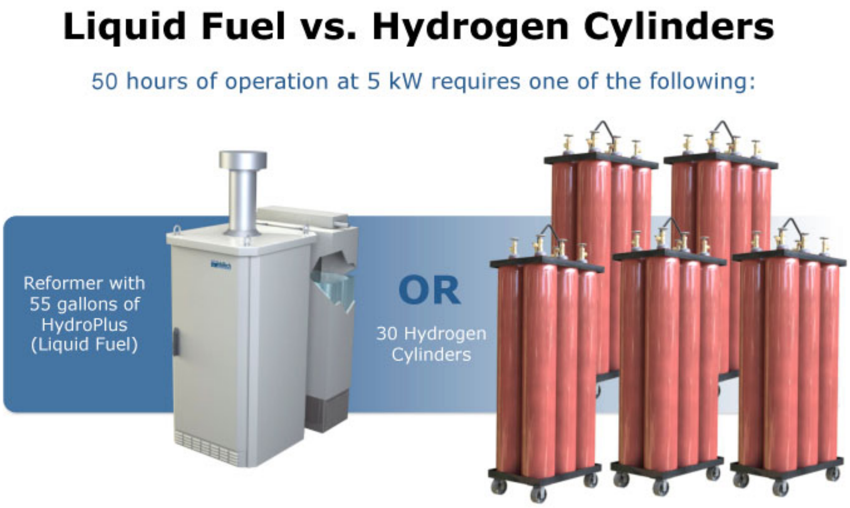



**Figure 4: Liquid fuel reformer vs. hydrogen cylinders.**

The fuel distribution channel for HydroPlus is developing quickly, and the fuel can be ordered and shipped directly from manufacturers as needed in five- and 55-gallon drums. Qualified HydroPlus liquid fuel distribution partners are available worldwide including in North America, Latin American, Europe, Middle East, Asia Pacific, and Africa.

## 5 How Fuel Processors Work

IdaTech has developed fuel processors for a variety of common fuels including HydroPlus, a methanol and water liquid fuel found in windshield washer fluid and many other common products. A fuel processor uses a liquid fuel to make hydrogen on site and on demand. Fuel processing is the act of converting hydrogen rich fuels into pure hydrogen gas as needed, then feeding the pure hydrogen directly into a fuel cell stack.

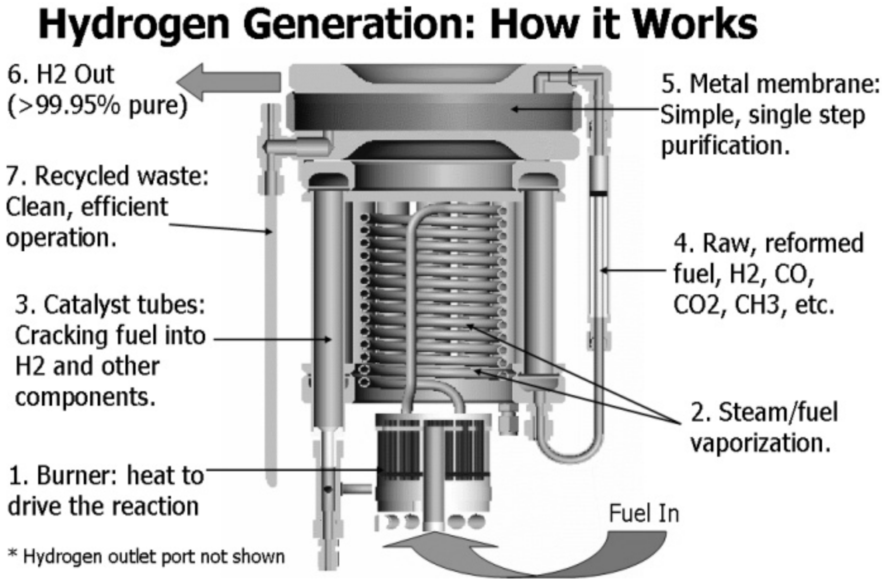



**Figure 5: Fuel processor.**

Fuel cell systems with liquid fuel processors can provide backup power for days instead of a few hours by using energy dense liquid fuel.

To create power, the fuel cell system first activates a burner to drive the reaction, followed by fuel vaporization. Within the catalyst tubes, the fuel is broken into hydrogen molecules and other components. From there, the raw reformed fuel ($H_2$, CO, $CO_2$, etc.,) is purified by the metal membrane, and the waste elements are recycled in a clean, efficient operation, producing 99.9+% pure hydrogen. The key differentiator in the fuel processing stages is the hydrogen purification method.

## 6 Fuel Cell Installations

Backup power fuel cell systems have been installed at telecom base station sites worldwide. These installations have shown the benefits and ease of fuel logistics for fuel cell systems that run on liquid fuel. Fuel cell systems with built in fuel processors and integrated 220 liter fuel tanks can operate without interruption for 50 hours at full output (5 kW). Fuel can be easily stored, transported onsite and units can be re-filled even while in operation. Fuel is stored locally for rapid dispatch to sites when needed.

## 7 Replacement of VRLA Batteries and Diesel Generators

As can be seen traditional solutions aren’t always appropriate for sites requiring extended run times (days vs. hours), and don’t always work. VRLA batteries, for instance, are suitable for typical eight hour run times.

Generators have significant limitations in that they add to overall backup power system cost and space requirements, they are increasingly difficult to install on-site due to significant noise and emissions, and have high maintenance requirements. Other benefits fuel cell systems have over traditional solutions like VRLA battery strings or diesel generators include operation in a larger temperature variance, lighter weight, longer life expectancy and greatly reduced maintenance intervals, reduced emissions and hazardous waste, are easily scalable, and have the option for remote monitoring and control.

## 8 Summary

In summary, fuel cell backup power systems operating on a compact liquid fuel can remove the challenges that hydrogen-only systems face. Whether the challenge is hydrogen delivery and storage due to a remote or roof-top location or the high price of hydrogen, reformer-based fuel cell systems have numerous advantages versus hydrogen-only systems as well as traditional battery strings or diesel generators.

In addition to those benefits, the compact liquid fuel allows virtually unlimited fuel cell backup power. Existing solutions are commercially available today for mission critical and remote sites, such as telecommunication carrier’s tower sites and other critical communications networks. Backup power for critical telecommunication applications is an example of the range of solutions that can be addressed today using fuel cell and reforming technology.

# 250 $W_{el}$ Reformer Fuel Cell System for Bio-Ethanol

**Thomas Aicher**, Johannes Full, Gerard Kraaij – Fraunhofer Institute for Solar Energy Systems ISE, D-79110 Freiburg, Germany

Researchers at the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg developed a fully automated ethanol reformer fuel cell system in cooperation with several partners from industry. The electric power output of the system is 250 Watt. The system is fueled by denatured bio-ethanol. This fuel is renewable, inexpensive, non-toxic and commercially available to users throughout the world. One of the various applications is the off-grid power supply for medical equipment in emerging and developing countries.

The ethanol reformer fuel cell system can be used outdoors and operates at ambient temperatures ranging from -10 to +40°C. At the push of the start button, the electric power becomes available to the customer. A buffer battery is used during the start-up phase, when hydrogen is not yet flowing to the fuel cell. The technology demonstrator system including the tank has a total volume of 195 l and a weight of 35 kg, respectively. As shown in Figure 1, it consists of four modules (fuel cell, reformer with gas purification, electronics and tank). It has the potential for significant reduction in volume and weight. The main system functions are carried out by:

- a reformer with gas purification. The latter reduces the amount of carbon monoxide in the reformate gas to a level that is suitable for the following PEM fuel cell.
- a commercial low-temperature PEM fuel cell, which was optimized by the Fraunhofer researchers for operation with a reformate gas (product gas of the reformer).
- a tail gas combustor in which the off-gas from the anode is oxidized and provides the heat needed for evaporation and overheating the feed streams (ethanol, water and air).

The reformer system includes an autothermal reformer, high and low temperature shift reactors, a selective methanation reactor, a combined start-up and tail gas combustor, and a commercial PEM fuel cell (as depicted in Figure 2). A minimum amount of process controls and little internal heat integration kept system architecture simple. It has to be noted, that maximizing system efficiency was not a foremost design objective.

Process simulations provided optimal operating parameters, expected hydrogen yield, and system efficiency. The reformer temperature was selected to be 730 °C with minimal methane production and no soot formation in the reactor. The oxygen-to-carbon ratio (O/C) is determined by the temperature of feed streams, reforming temperature and heat losses. It was set to be in the order of 0.9. The steam-to-carbon ratio (S/C) has no significant impact on carbon monoxide concentration in the reformer system product gas, i.e. at the outlet of the selective methanation reactor. Therefore, S/C was selected to be 2.5, sufficiently high to avoid soot formation in the reforming reactor and yet small enough to keep the size of the water evaporator in a sensible range.

**Figure 1: Mobile ethanol reformer fuel cell system for 250 W electric power output.**

## Reforming System Design

### Steady State Operation

At first, we operated the reformer fuel cell system in a lab environment and investigated all reactors thoroughly. We optimized start-up and shut down procedures to minimize degradation of the catalysts. Finally, the complete reformer fuel cell system was integrated into four separate modules, and placed in one housing (refer to Fig. 1).

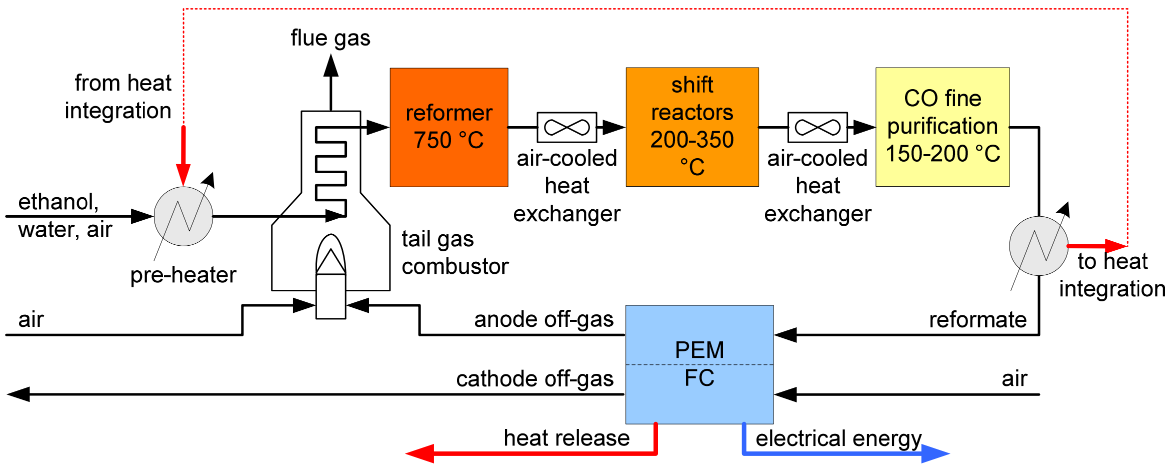



**Figure 2: Process flow diagram of the ethanol reformer fuel cell system.**

We operated the ATR test rig with constant operating parameters during various test campaigns up to 5 hours, accruing a total of over 150 hours on stream. Figure 3 shows the gas composition measured by on-line gas analysis for a typical test run. The dry gas composition at four locations throughout the reformer system is plotted over run time: at the outlet of the SelMet reactor, of the LTS and HTS and of the ATR itself. At each location the gas was analyzed for about ten minutes in this test run, before switching to the next sampling port upstream.

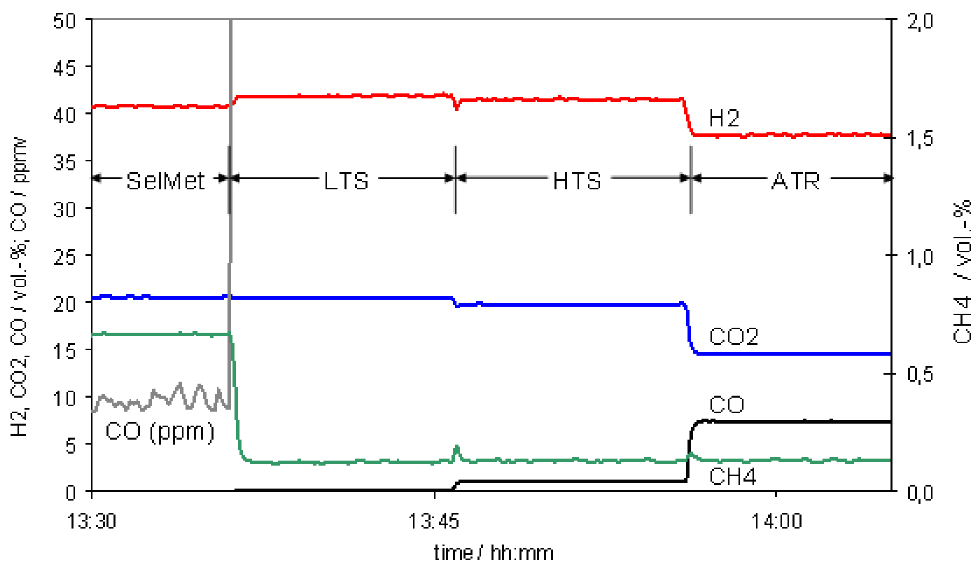



**Figure 3:** **Gas composition (dry basis) measured by on-line gas analysis at various locations in the reformer systems. Operating parameters: S/C = 2.5, gas temperature at ATR inlet = 390 °C, O/C = 0.9.**

Starting at the right hand side, the gas at the ATR outlet contains (on a dry basis) approx. 37.6 vol.-% H2, the catalyst outlet temperature was 745 °C. This gas is cooled down in an air cooled heat exchanger to 420 °C and leaves the HTS with about 400 °C. The gas at the HTS outlet consists of approx. 41.5 vol.-% H2. This catalyst demonstrates a very good shift activity reducing the CO content down to 1.0 vol.-% (dry). Prior to entering the LTS the gas is cooled down again in an air-cooled heat exchanger, this time the reactor inlet temperature is 290 °C. The LTS product gas leaves the reactor with a temperature of 280 °C. The SelMet catalyst, finally, is operated at a catalyst inlet temperature of 230 °C. The temperature decrease over the reactor length is about 10 K. The data confirm that the CO concentration is in the order of 10 ppmv, well below the specified value of 20 ppmv. The methane content in the gas stays below 0.7 vol.-% (dry basis) providing a selectivity of 65% for the SelMet catalyst in the selected temperature range. For further details see Aicher et al. (2009).

**Operation with PEM Fuel Cell**

We use a PEM fuel cell from Schunk Kohlenstofftechnik GmbH which delivers a nominal power of 360 W when operated with pure hydrogen and fully humidified gases on both sides. If operated with water saturated reformate on the anode and ambient air on the cathode we reached a power of approximately 300 W as shown in Figure 4. One reason for the reduced power are the trace amounts of CO in the reformate gas, which occupy some of the active centers of the anode catalyst. To minimize this effect we add at times small amounts of air to the reformate gas before the anode with an air bleed pump. This reduces the deactivation of the catalyst by oxidizing the CO. However, it has to be noted that the additional air not only oxidizes the CO but some hydrogen as well. A second reason for the reduced power output compared to operating the fuel cell with pure hydrogen is the presence of $CO_2$. Small amounts of this component are converted in the fuel cell into CO by the shift reaction, that cannot be removed by air bleed. This is not a serious problem because the remaining catalyst sites are sufficient for fuel cell operation.

The observed fluctuations in stack voltage stem from flooding effects on the anode side as the reformate gas is fully humidified. We remove accruing water drops within the anode flow channels by purging the anode r, which means that the anode off-gas is released to the ambience for some milliseconds. The resulting fluctuations in stack voltage are smoothened by the DC/DC converter.

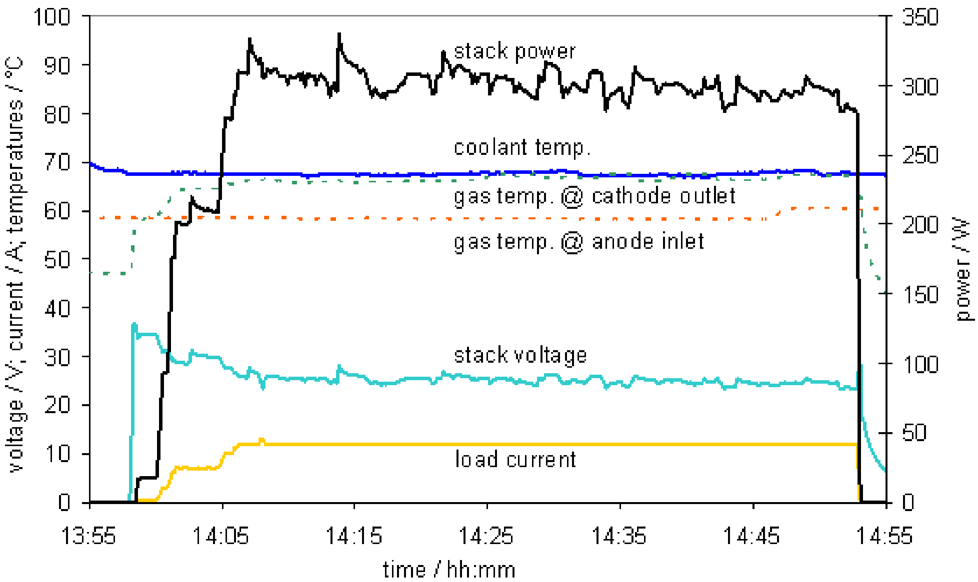



**Figure 4: Fuel cell operating data measured during operation with reformate gas using a $H_2$ stoichiometry of 1.25 and the air stoichiometry on cathode side being 2.5. Operating parameters of the reformer system: S/C = 2.5, gas temperature at ATR inlet = 390 °C, O/C = 0.9.**

## Reference


[1] T. Aicher, J. Full, A. Schaadt, “A Portable Fuel Processor for Hydrogen Production from Ethanol in a 250 $W_{el}$ Fuel Cell System”, Int. J. Hydrogen Energy, available online, DOI information: 10.1016/j.ijhydene.2009.07.064

# Solar-hydrogen Based Autonomous Electric Power System in Operation

**Matthias Brinkhaus**, **Dieter Jarosch**, **Jörg Kapischke**, Energy and Environmental Systems Engineering, University of Applied Sciences Ansbach, Germany

**Abstract**

This study presents a solar-hydrogen based autonomous electric power system installed at the University of Applied Sciences Ansbach; and its operational characteristic. The system is comprised of photovoltaic modules, inverters, an electrolyzer, a hydrogen energy storage and a fuel cell. Such off-grid power supply stations which are based on sustainable energy sources can reduce carbon dioxide emissions and can operate during darkness. The aim of this project is the reduction of costs of the system in order to get a competitive autonomous electric power supply. The energy balance and the conclusion are presented as well as a look into the future.

## 1 Introduction

As the proportion of renewable energies grows, energy storage and intelligent energy management are becoming increasingly important [1, 2]. The irregular energy output and the large number of decentralized regenerative power plants contribute to this development. Owing to two fundamental trends in Germany – the declining proportion of fossil and nuclear energy sources and the increasing share of renewable energy – the demand for energy storage capacity will rise within the next decades [3]. Studies reveal that in regions without connection to public energy grids, small energy grids are sensible and practicable [4]. In this connection the storage of fluctuating energy is particularly important [5].

With its high specific storage density, high degree of environmental compatibility and storage capacity without loss, hydrogen is a favourable energy carrier. Surplus energy from fluctuating energy sources can be converted into storable hydrogen (6). This would ensure a maximum degree of independence from fossil resources, from public grids as well as wind and irradiation conditions. In the long run hydrogen will continue to gain in importance in the energy industry [7].

The off-grid power supply system at the University of Applied Sciences in Ansbach consists of a photovoltaic array, inverters, an electrolyzer, batteries, a hydrogen tank and a fuel cell. This system forms an island grid which supplies conventional electrical consumers with energy at any time independently from the public grid. Firstly the energy demand is covered by the PV array; the batteries are charged by surplus energy and hydrogen is produced for long-term storage. At times of low performance of the PV array hydrogen is reconverted in electrical power. The long-term hydrogen-based storage system permits the use of smaller solar module surfaces and is a reliable way to provide supply security during periods of low renewable energy output. In this connection, supply security means that at any given time the entire power demand must be covered by the storage system as the PV array would not be generating any power. Thanks to its modularity, individual components of the system can be scaled as needed. In this way varying demands concerning performance, storage capacity and costs can be met. Additional generators and loads can easily be connected to the island grid based on alternating current. The objective of the island grid at the University of Ansbach is to provide practical evidence for a sustainable and secure power supply based on conventional components and renewable energies.

## 2 Experimental System

The autonomous island grid consists of conventional components (see figure 1).

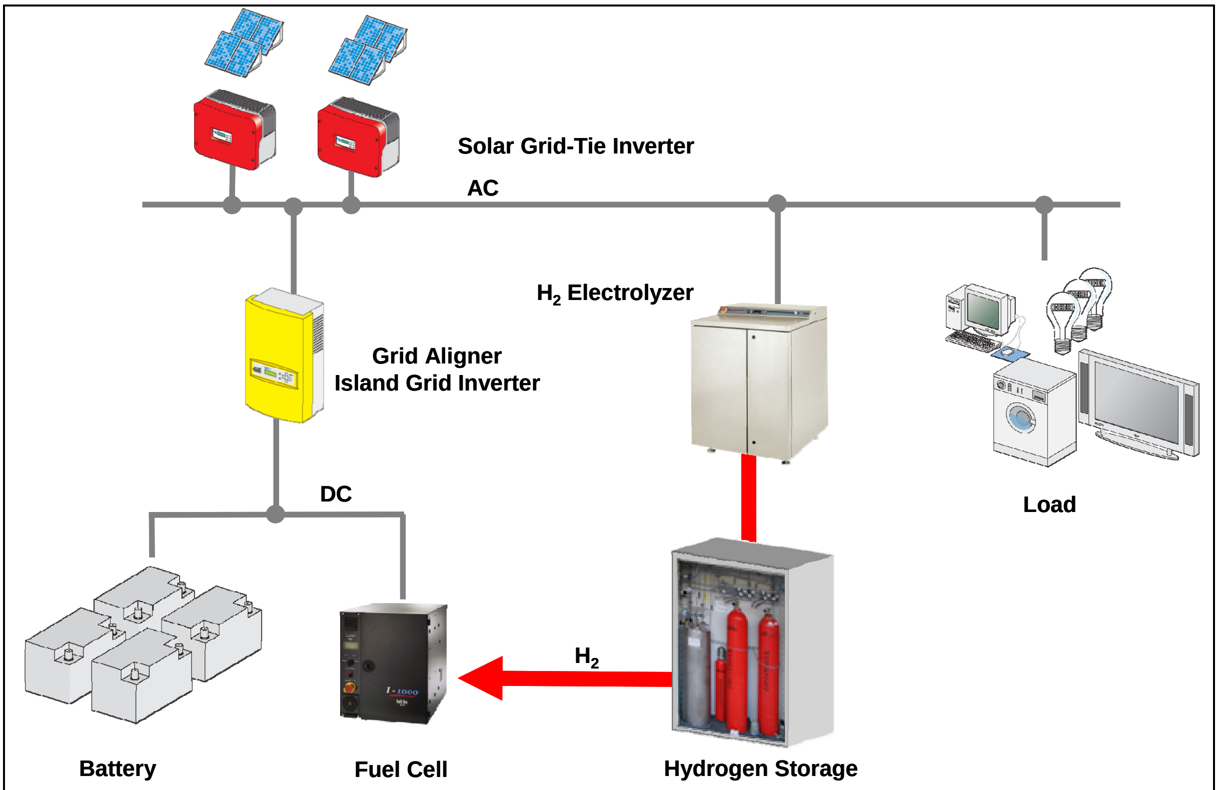



**Figure 1: Solar-hydrogen based autonomous electric power system at the University of Applied Sciences Ansbach.**

Electrical consumers are supplied by the PV system installed on the roof of the university.

Inverters convert direct current from the modules into alternative current for the island grid. A grid aligner and an energy storage system ensure stability of the 230-VAC island grid. Electrical consumers can be directly connected and supplied with this energy.

The storage system of the plant consists of an electrolyzer, a hydrogen tank, a fuel cell and lead batteries (see table 1). In an electrolyzer hydrogen is produced from water using excess solar energy. The adjustment to the available excess energy is achieved through the controlled hydrogen current of the electrolyzer and grid frequency. When the energy demand of the electrical consumers is higher than the energy from the PV array the grid frequency drops. Below a frequency of 50 Hz the fuel cell is switched on. The fuel cell converts the stored hydrogen in electrical power. The lead batteries serve as short-term energy storages. They immediately compensate supply irregularities. The current controlled inverters of the PV array require a reference value in order to be fed into the island grid. A bidirectional, self-commutated battery inverter serves as grid aligner. On the AC side it regulates current, frequency and power. On the DC side it operates as battery charger with charging regulator and deep discharge protection by load shedding. The island grid inverter additionally converts direct current from the fuel cell and the batteries into alternative current of the island grid. The individual components of the system can be directly controlled and regulated by means of a PLC system (programmable logic controller).

**Table 1: Technical specification of solar-hydrogen based autonomous electric power system.**

| | | |
|---|---|---|
| PV Arrays | Power | 8,6 kWp |
| | Modules | 40 x IBC 215P SI, polycrystalline |
| Grid Tie Inverter | Type | 2 x Sunny Boy 3800, SMA |
| Electrolyzer | Type | PEM, "Hogen 20“, Proton |
| | Max. Pressure | 13,8 bar |
| | Power Consumption | max. 4 kW |
| | $H_2$-Production Rate | 0,5 Nm³/hr |
| | Efficiency | approx. 36% |
| Hydrogen Storage | Pressure | 200 bar |
| | Volume | 50 l |
| Fuel Cell | Type | PEM, I-1000, ReliOn |
| | Power | 1 kW |
| | $H_2$-Consumption | 1 Nm³/hr (1kW) |
| | Efficiency | approx. 39% |
| Island Grid Inverter | Type | SI 4248FC, SMA bidirectional |
| | max. Power | 4200 W |
| | | 230V, 50 Hz |
| Batteries | Type | VRLA, Hoppecke |
| | Capacity | 140 Ah, 12 V |
| | Quantity | 4 in series |
| | Weight | 218 kg |

### 24-Hour-test run

The functionality of the system was proved in several test runs. Figure 2 shows the measured values within a 24-hour-period from September 9 to 10, 2009, days on which irradiation values were considerably high. The load demand was based on an idealized single-household load profile. The total used solar module surface was 66 m², which is the equivalent of a power output of 8.6 kWp. The fuel cell supplied the loads at night. As irradiation values increased the performance of the fuel cell slowed down. During the day the power output from the PV array was so high that most of the time the electrolyzer operated at full load. As irradiation values declined in the evening the electrolyzer also slowed down and subsequently the fuel cell was activated again.

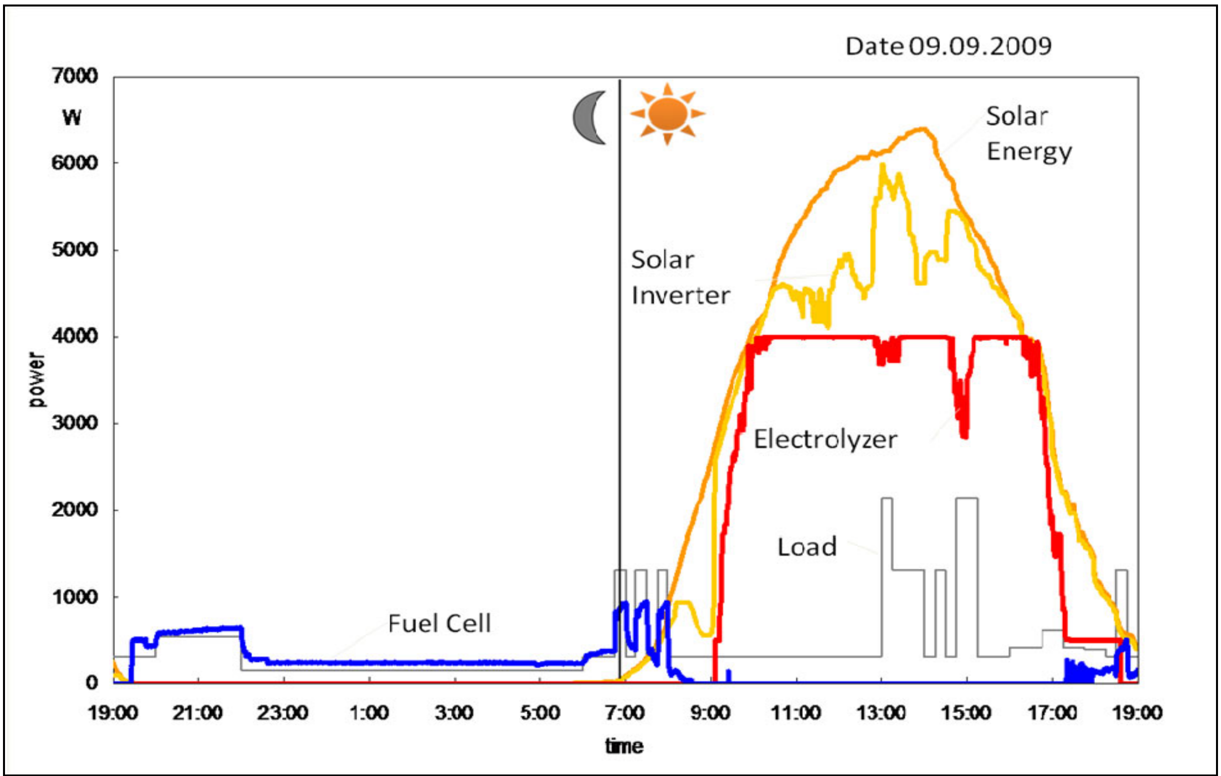



**Figure 2: 24-hour-test run.**

The PV array generated a total power of 38 kWh from 41 kWh of solar energy. The fuel cell supplied 5 kWh. The electrolyzer consumed 32 kWh and the regular load used 10 kWh. The batteries consumed 3-4 kWh/d (see figure 3).

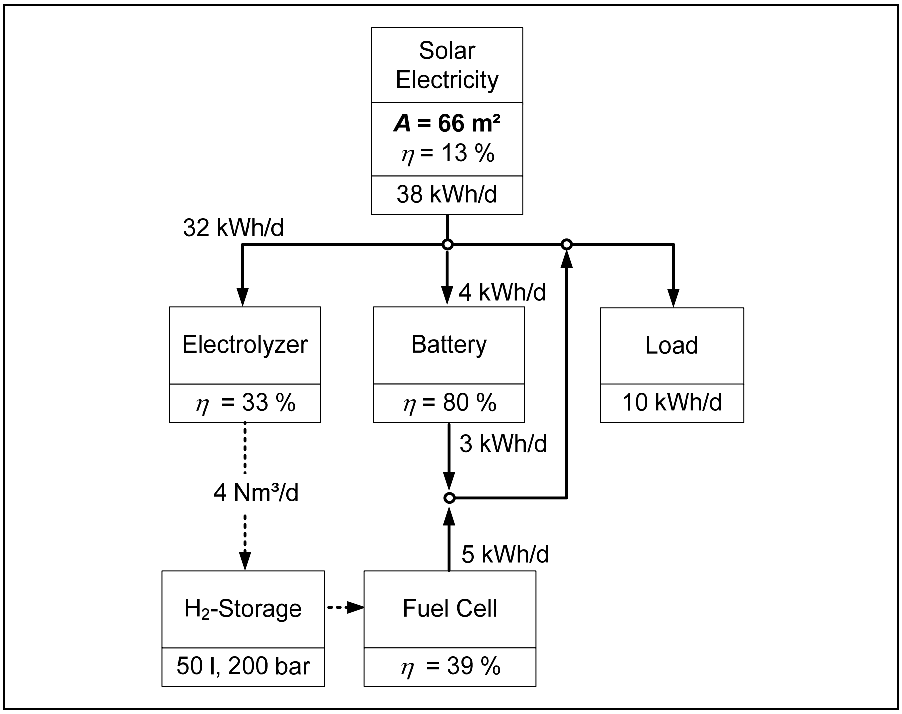



**Figure 3: Energy flow diagram based on 24-hour-test.**

## 3 Discussion

Power supply based on a hydrogen-battery system is environmentally friendly and sustainable. Such combined systems offer perfect supply security during winter, even independently from renewable energy sources. In comparison, battery systems can only compensate fluctuating energy from the PV array with a very large PV surface. In the case of a power failure over a longer period, an additional generator (e.g. diesel generator) is needed to supply the loads. The hydrogen-battery system, however, does not produce harmful emissions. Moreover thanks to smaller PV arrays, the costs for material and energy resources can be reduced.

Excess hydrogen storage can be used to complete partial charge cycles in lead batteries. While partial charges have no affect on hydrogen, they shorten the lifespan of the batteries. The combination hydrogen and battery provides a higher degree of cycle stability and ensures longer life spans of the batteries. This project demonstrates the advantages of stored energy from hydrogen in connection with the storage of fluctuating energy sources.

## 4 Conclusion

The selection of the components, the control of the system and the operational behaviour of the individual components have to be optimized.

In this connection future research will focus on island grid aligners in order to be able to store excess solar energy even more efficiently in the form of hydrogen. This is why the electrolyzer should be connected to the DC side of the grid aligner. Here it is recommended to use the stack voltage of the electrolyzer as the control variable.

The fuel cell and the electrolyzer currently require a total of approx. 600 W in standby mode. This should be reduced to a minimum. The components should possess autonomous switching behaviour to react to given input signals.

## 5 Outlook

The successful operation of the island grid demonstrates the functionality of the system. Further testing will focus on varying environmental and system parameters in order to verify optimization approaches. Special attention should be paid to improve the efficiency of the system so as to be economically competitive. Reliable models for dimensioning an island grid system must be developed further. Based on appropriate boundary conditions, hydrogen, as a long term energy store for excess electrical energy, can help opening up new fields of application for this very promising technology.

## References

[1] AGE-(Association of German Electrical Engineers): Energy Storage in Power Supply Systems Based on a Large Proportion of Renewable Energy Carriers

[2] Lagorse, Paire, Miraoui; A multi-agent system for energy management of distributed power sources; Renewable Energy 2010; 35; 174 - 182

[3] Zerta, Landinger, Schmidt; The Challenges of Energy Storage, Energy 2.0 Compendium 2010

[4] Engler, A. (ISET), Meinhardt, M., Wollny, M. (SMA Technolgie AG), AC Coupled Island Grids for Integration into Power Supply Systems of the Future, 2006

[5] Dötsch; Energie auf Abruf, Energie 2.0, July 2008, 52 – 54

[6] Ghosh, Emonts, Janßen, Mergel, Stolten; Ten years of operational experience with a hydrogen-based renewable energy supply system, Solar Energy 2003; 75; 469 - 478

[7] Lipman, Edwards, Brooks; Renewable Hydrogen – Technology Review and Policy Recommendations for State-level Sustainable Energy Futures; University of California – Berkeley, 2006

# Remote Telecom System Including Photovoltaic Energy and $H_2$ Production by Electrolysis

**Esther Chacón**, **Raquel Cuevas**, **Graciano Martínez**, **Guillermo Gómez**, National Institute for Aerospace Technology, Spain

**Abstract**

The use of renewable energy is growing in significance due to exhaustion of fossil fuel and the environmental risks of its extensive use. There are a lot of applications in which fuel cell advantages play an important role as in the remote telecom applications.

There are thousands of units of telecom equipment without possibility of grid connection. These equipments are usually fed with photovoltaic panels, using batteries as energy storage systems that require to oversize these systems. The utilization of hydrogen to operate PEM fuel cells could let to reduce the size of this subsystem.

The objective of the project is the creation an independent system based on the use of PEM fuel cell in order to supply energy for a telecom system. It includes an electrolyser, and the hydrogen produced will be stored in metal hydride canisters for a final use into a fuel cell.

## 1 Introduction

We all know that we are heading to a shortage of energy sources, particularly fuel oil. The developed countries are directing their energy policies towards three fundamental parameters, these are the following: to ensure the fuel supply, the fulfilment of environmental agreement and economical competitiveness. The energy situation in Europe including the future energy demands and the few sources of own energy force the European economy to take a position of high risk. The combination of using solar-based energy generation and hydrogen as an energy carrier and storage offers a sustainable solution to many aspects of the energy issues, including transport and electricity generation. The hydrogen could be the dominant fuel, converted into electricity in fuel cells, leaving only water as waste product. Hydrogen is the most abundant element in the universe but it is not really an energy source like oil and coal because it is almost never found in its pure form. It must be released from chemical compounds. One method is to separate the oxygen and hydrogen from water by using electricity, a process known as electrolysis. As chemical reaction is reversible, the combination of hydrogen and oxygen will produce energy and water. This is the process used in an energy device known as a fuel cell. The most important aspect of this entire process is to produce hydrogen very economically. The hydrogen is not freely available in nature in large quantities, so it must be produced by conversion of other energy sources, including fossil fuels and renewable energy. Only renewable based hydrogen production can contribute to $CO_2$ emission reduction. Current renewable production methods of hydrogen include H2 production from biomass, from water by electrolysis (where the electricity has been produced by wind, solar or hydro energy).

## 2 Hidrosolar $H_2$

### 2.1 General description

The installation's main feature is its great modularity. The modularity will allow us to form it in different ways depending of the weather conditions and the parameters which we want to change.

The installation is designed to provide electrical energy to a remote telecom system. The energy primary source is the sun and the PV panels provide energy from solar radiation to storage system as electricity. We have two methods of energy accumulation: lead acid battery system and hydrogen storage system by metal hydrides.

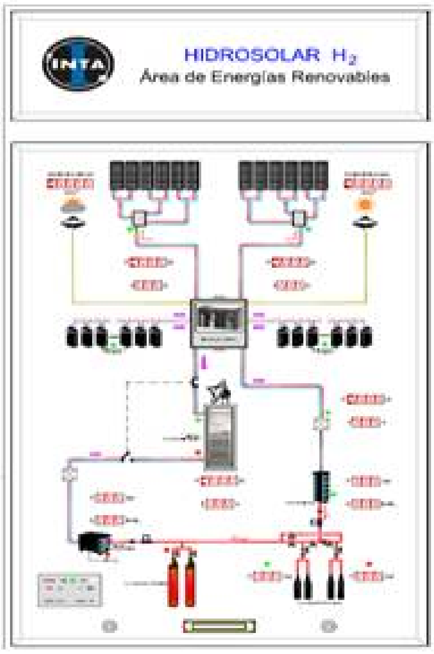



**Figure 1: Hidrosolar $H_2$.**

This last subsystem of storage needs the addition of a fuel cell which transforms the hydrogen to electrical energy when the installation needs it.

All the installation components are described in tables 1 and 2:

**Table 1: Subsystem 1.**

| System element | Characteristics |
|---|---|
| 6 PV panels | 1.5 Wp, slope 60º, south |
| 12 batteries | Lead-acid 6 EAN 55 |
| Control system | Download data and control performance |
| Telecom system | Load 145 W, Load peek 197 W |

The subsystem 1 is used to feed the telecom system by means of the traditional system and it will be helped by the batteries of the subsystem 2 in case of running out of energy.

**Table 2: Subsystem 2.**

| System element | Characteristics |
|---|---|
| 6 PV panels | 1.5 Wp, slope 60º, south |
| 12 batteries | Lead-acid 6 EAN 5 |
| Control system | Download data and control the performance |
| Telecom system | Load 145 W, Load peek 197 W |
| Inverse DC/AC | Performance max. 93% |
| 4 hydrides metal canister | Capacity max. 940 l and pressure between 3.5 and 17 bar |
| 2 pressure hydrogen canister | Auxiliary. |
| Fuel Cell | 1200 W, pressure hydrogen 0.7 to 18 bar |
| Electrolyser | 300 VA max., hydrogen flow 0.5 l/min. |

The subsystem 2 is dedicated to the production of hydrogen by electrolysis. Normally the batteries supply energy to the electrolyser, the hydrogen is stored in hydrides metal canisters and, when the load requires it, the hydrogen is going to fuel cell to produce the electrical energy necessary to feed the remote telecom system. The only exception is when the subsystem 1 has not the necessary energy and the subsystem 2 lends its batteries to feed the load.

## 2.2 The characteristics of the main components

The photovoltaic panels are connected to provide a peak power of 1.5 kW and nominal voltage of 24 V with 12 modules, 6 modules of 2 series panel. They are solar modules of ATERSA, with 7.28 A. and 17.48 V. in mpp.

The PV modules are connected to a lead acid battery system with a capacity of 396 Ah. This system is composed by 24 batteries, 12 connected in series to provide energy to load and 12 connected in series to provide energy to electrolyser. Each one has a voltage of 2 V, therefore 12 batteries for total voltage system of 24 V.

The electrolyser has been developed by SCHMIDLIN. The electrolyser employs the newest membrane technology available for electrolytic production of pure hydrogen gas. This technology is preferred over alternative hydrogen generating techniques because is clean and requires less maintenance. Furthermore, an auto shut off procedure places the unit in standby in the event of an internal error and selectable alarms allow the user to be informed whenever operating conditions vary from the set point.

Metal hydrides are certainly the safest way to store flammable hydrogen gas. The Ovonic Metal Hydride has been developed by Ovonic Fuel Cell Company. Typical metal hydrides are powders. When these metal powders absorb hydrogen to form hydrides, heat is released. Conversely, when hydrogen is released from a hydride, heat is absorbed.

Figure 2: PV panels.

Figure 3: Electrolyser.

The absorption process consists of Hydrogen gas molecules ($H_2$) stick to the metal surface and break down into hydrogen atoms (H). The hydrogen atoms then penetrate into the interior of the metal crystal to form a new solid substance called a "metal hydride". The metal atoms are usually stretched apart to accommodate the hydrogen atoms. The physical arrangement (structure) of the metal atoms may also change as the hydride forms. The desorption process. Hydrogen atoms migrate to the surface of the metal hydride, combine into hydrogen molecules ($H_2$) and flow away as hydrogen gas. The metal atoms contract to form the original metal crystal structure.

The absorption is similar to the storage of electricity from a battery. The advantages are the following: fast and simple charge, even after prolonged storage, high number of charge/discharge cycles, good low temperature performance and good load performance.

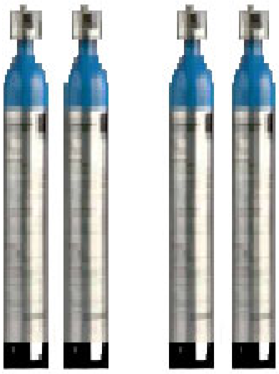


Figure 4: Hydrides metal.

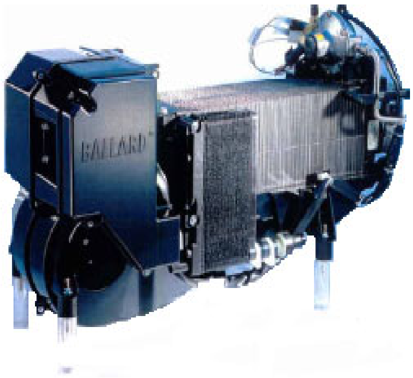



Figure 5: Fuel Cell Ballard.

The Nexa power module contains a BALLARD fuel cell stack, as well as all the ancillary equipment necessary for fuel cell operation. The fuel cell provides up to 1200 watts of unregulated DC power at a nominal output voltage of 26 Vdc. It is extremely quiet and produces zero harmful emissions. The fundamental component of the Ballard fuel cell consists of two electrodes, the anode and the cathode, separated by a polymer membrane electrolyte (PEM fuel cell).

The PEM fuel cell stack operates at low pressure, minimizing parasitic losses, reducing noise and enhancing system reliability.

The Nexa fuel cell stack architecture does not require external fuel humidification and it is air-cooled. Furthermore, it will shut down if a cell failure or a potentially unsafe condition is detected in the fuel cell stack.

In order to control all the system we have a programmable robot, which is included within a synoptic. This synoptic indicates us the system state at any time because it contains a scheme of the installation and by means of LEDs (LEDs green) it indicates us the state of each element (ON/OFF).

The working of Hidrosolar $H_2$ is testing the use of PEM fuel cell in remote telecom application. When the right operation was assured in the laboratory, it was integrated to the rest of the components in the test field.

To monitor the performance of the whole system, specific software is developed from t2s S.L which is included in the programmable robot.

After the big difficulties encountered during the integration phase with the fuel cell due to its sensibility to the operational parameters we are in phase of data analysis in operational period, studying the results and the possible causes of bad operation system.

The monitorization is able to assure the security and an effective control because it communicates via telephone in case of any unexpected trouble.

## 3 Preliminary Simulation

TRNSYS 16 was used to simulate the Hidrosolar_H2 system. TRNSYS is used by engineers and researches around the world to validate new energy concepts, and it allow us simulate the behaviour of our installation.

As a previous step to the whole TRNSYS simulation, all installation elements were validated. To determinate the most efficient configuration of Hidrosolar $H_2$, the system was simulated changing some characteristic parameters. The final conclusion was that the optimum configuration is using the hydrogen part of feed system as an auxiliary energy in periods of time with little solar radiation. In periods of time with much solar radiation the load is feed by PV panels, the excess of radiation is stored as hydrogen, mainly in summer.

## 4 The Future Project

Within the immediate future of the project several routes of performance are planned. The first one will be the change of the system parameters; in order to evaluate the possible reduction of batteries and PV panel's size, evaluate the minimum hydrogen required, the endurance of the fuel cells, and so on. This fact will suppose an increase of the feeding capacity of our installation and it will be possible to be directed to locations with greater consumption.

The second one will be the components optimization to achieve the dynamic management of energy.

Later, if we shall obtain an economically profitable installation, it will be studied the possibility of introducing this system in the energy market to feed a remote system without possibility of grid connection.

## 5 Conclusion

Although the simulation recommendation gives us a different configuration, we are interested in the behaviour of the hydrogen subsystem, and by that reason, we oblige the installation control to work with the half of PV panels in the hydrogen subsystem (feeding the electrolyser).

When the installation had been working during a year we would have data enough to configure the system parameters again within the most efficient installation. Furthermore, the system modularity will help us to change the configuration whenever we need.

The use of hydrogen with PV panels instead of diesel generator decreases the pollution and the maintenance activity and increases the availability of the telecom equipment.

Although the behaviour of this system during the summer period will show us the panels size is bigger than it needs, at the beginning this configuration is the best option to assure the necessary hydrogen production that will feed the load during winter period.

## References

[1] Argumosa, M.P, Schucan, T.H. Fuel Cell Innovative Remote Energy System for Telecom (FIRST).

[2] Marchetti, C. and N. Nakicenovic (1979). The Dynamics of Energy Systems and the Logistics Substitution Model. IIASA, RR-79-13, Laxemburg, Austria

[3] Goltsov VA, Veziroglov TN, (2001). From hydrogen economy to hydrogen civilization. International Journal of Hydrogen Energy 26:909-462

[4] Coxke (1976) Hydrogen from solar energy via water electrolysis. Proc 11th IECEC pp. 926-932

[5] Esteve D, Ganibal C, Steinmetz D, Vialason A, (1980) Performance of a photovoltaic electrolysis system. Proc 3rd Word Hydrogen Energy Conference, Tokyo V. 3, pp. 1583-1603.

# Fuel Cells as Back-up DC Power Supply for Substations

**Martin Hölscher**, H&S- Hard- & Software Technologie, Germany
**Gerd Bittner**, Hochschule Ruhr West, Germay
**Peter Rümenapp**, Amprion, Germany

Continued reliable operation of substations is essential if the high voltage grid should fail. A battery with a high but finite capacity supplies the auxiliary power required in such a case. A sustainable redundancy concept also suitable for longer grid failures is required, in particular for strategically important substations. An innovative and promising solution is the application of fuel cell systems. Amprion, the plant operator and the Dortmund-based H&S system vendor have implemented this concept in a pilot plant for an existing high voltage substation. The following article describes the specific construction of an innovative emergency power supply for an application with particularly high demands.

## 1 DC Power Supply in High Voltage Substation

Switches and control systems in high voltage substation must remain operational without restrictions even if the high voltage has a fault or fails completely. The required auxiliary energy stems from stationary lead-acid cells – pooled into a battery using cell connectors – with a nominal voltage, e.g. 220 V DC, and a very high capacity that can sustain switching operations for several hours. Accordingly, all devices and systems are rated for an operating voltage of 220 V DC. During normal system operation, a rectifier constantly charges the battery in the “stand-by parallel mode” via the grid. To dimension the DC supply of a system, great care must be taken not only to ensure a sufficient stand-by time in case of an error but also that the peak currents the switchgear draws can be provided during switching. The battery system must be able to supply such peak currents in particular when the end of the rated stand-by time is near.

## 2 Limits of Conventional Redundancy Solutions

The concept of an emergency power supply using a battery with a large capacity has proven its worth for many years. But in case of an error such as a longer power outage or a defective charge rectifier, time is always pressing because the only energy source of the substation is the battery with its restricted capacity. A sustainable redundancy concept is of major importance, in particular with strategically vital substations representing a nodal point for the reliable large-area power supply of a region. Determining factors are, for example, typical failure probabilities and associated failure times or replacement and installation times of defective rectifiers or other defective devices. The operators are constantly testing new alternatives in order to keep the system operable in a reliable manner and for an extended period of time or to optimize repair assignments or the storage of spare devices should a power outage occur. An innovative and technically feasible solution is the use of fuel cells to be described in detail below.

## 3 Application of Fuel Cell Systems as DC Power Supply

Fuel cells convert the energy stored in hydrogen to heat and electrical current. Commercially available systems [1] feature an electric power of 5 kW at a DC voltage of 48 V. A downstream DC/DC converter [2] provides the operating voltage of 220 V DC required in this area of application. A nest of, for example, 12 hydrogen cylinders in a skeleton container ensuring a load-dependent operating reserve for one day supplies the “refillable” energy. Even longer system failures can be bridged without being put under any time pressure since organizing the supply of hydrogen is easy. When an agreement with a reliable supplier of hydrogen and an appropriate defined lead time are in force, this supply could even be automatically triggered by a direct request from the system.

Relatively budget-priced PEM fuel cells with a rated service time of approx. 1500 operating hours per stack are especially suited for this kind of emergency power supply. A single test run for a few minutes each month is sufficient to ensure its operability and also to prevent dehydration of the stack. The service life of such a solution is more or less equal to the 15 years of stand-by service life specified by the manufacturer.

With a reliable supply of hydrogen and independent of the installed battery capacity, this new type of a compact and, above all, emission-free and silent emergency power supply for large scale switchgear ensures a nearly unlimited supply in case of a malfunction. A practical dimensioning example: a 5 kW PEM stack supplied by a nest of 12 hydrogen cylinders (200 bar) can run for approx. 24 hours at 220 V DC and a rated consumer load of 20 A. The regular and almost wear-free test runs give rise to high expectations with regard to reliability and long-life cycle. In addition to major maintenance scheduled at longer intervals, the fuel cell system starts its test runs fully automatically and reports detected errors to the remote control center.

## 4 Integration into Existing High Voltage Substation

For many years, the H&S system vendor headquartered in Dortmund [3] has been a partner of renowned electric power companies, also focusing on designing and marketing DC systems providing auxiliary power to switchgear. At present, H&S is engaging in the innovative field of fuel cell technology and assessing the field utility in the described area of application. Being a cooperation partner, Amprion GmbH [4] commissioned the installation of a fuel cell system with necessary peripherals for existing high voltage substation.

A fully-featured test installation on the company’s premises comprising hydrogen cylinder nest, 5 kW fuel cell system, DC/DC converter (48 V/220 V), rectifier, station battery, infeed/isolation cabinet, simulated secondary devices and monitoring technology made it possible to determine a great numbers of operating parameters and installation prerequisites beforehand. Examples: Adjustment of the messaging and start-up behavior of the fuel cell, specification of suitable redundant DC/DC converters with defined harmonic wave characteristics, connection to an existing alarm and warning system, adjustment of pressure sensor switching points, compliance with common operating and installation regulations, etc.

The rectifier converts the grid supply voltage (400 V AC) to 220 V DC during regular, trouble free operation. This direct current provides power to the secondary devices in the switchgear and also charges the station battery connected parallel as energy buffer. When an error such as a grid failure or a rectifier fault occurs, a second redundant DC infeed via the fuel cell and the DC/DC converter is available, which takes over the supply of the secondary devices via an existing low-voltage high-power fuse within the rated limits. The battery is still providing current peaks occurring when several switches start up at the same time.

In an article to follow, the authors will report on practical experience with the installed system and give a preliminary assessment of the solution's cost-effectiveness and the definite prospects.

## References

[1] Rittal, Herborn; www.rittal.de

[2] Powertronic Industrielle Leistungselektronik; www.powertronic.de

[3] H&S Hard- und Software Technologie, Dortmund; www.hstech.de

[4] Amprion GmbH; www.amprion.net

[5] Bittner, G.; Nowak, D.; Rümenapp, P.: Brennstoffzellen in der Gleichstromversorgung von Schaltanlagen, etz 1/2009

# Off-Grid Energy Systems with Fuel Cell Technology: A Challenge for Technical Training

**Klaus Rupprecht**, **Kilian Frank**, Heliocentris Energiesysteme GmbH, Germany

## 1 Introduction

Renewable energies are already considered a solution today for dealing with the expected energy shortage in the 21st century. The hydrogen-based fuel cell is part of this solution. As a complementary technology, it will be used in future off-grid energy systems together with hydrogen generators and hydrogen storages, forming a reliable and clean storage solution for sustainably generated energy.

The ability to combine different energy sources, storage technology and loads to an autonomous energy system granting the same security of energy supply as a user could expect from the national grid will be the key qualification requirements of tomorrow's system integrators. Both energy management know-how and profound knowledge about the diverse energy generation and storage technologies must therefore become part of today's technical training. It has to familiarize the engineers of tomorrow with this technology.

## 2 Off-grid Energy Systems for Learners

Based on its experience as a system integrator for energy storage solutions with fuel cells and batteries as well as the development of didactic equipment for technical training, Heliocentris has developed a full-fledged hybrid and off-grid energy system, which is tailored to conveying practical knowledge in the field of energy management – the New Energy Lab.

The system combines renewable energy generation from solar, wind and fuel cell power with modern energy storage technology to create an autonomous hybrid system. Optimized for the requirements of universities and vocational schools, the technology can be explored as a single process or at the level of the overall system. The system generates enough power to operate typical household appliances.

Learners can set up an autonomous power supply and learn about the interrelationships of various aspects of power management by experimenting with the parameters of the system components. The public power supply grid can be used as a backup to simulate the combined use of renewable and conventional energy sources, such as a diesel generator. The system can be used to simulate and analyze typical scenarios, such as operation at night or during periods of no wind. Extensive measuring technology, central monitoring and control software and an electronic load make it possible to record characteristic curves and system data.

The range of features and the components to be included in the system can be customized to suit individual requirements of the academy or technical training centre.

The system forms the basis for several learning objectives:

- Introduction to solar, wind, and fuel cell technology
- Design of hybrid systems

- Operation of hybrid systems
- Examination of renewable energy sources
- Autonomous operation of real-world consumers
- Observation of different scenarios: night-time operation, periods of no wind, peak loads

## 3 Energy Lab Components

Especially for institutions with departments entirely dedicated to renewable energy studies, the system offers various advantages. Unlike regular training equipment, which usually resembles the reality on a smaller scale, the New Energy Lab is a real energy system. Training can therefore be conducted in a realistic setting. The system includes measuring technology feeding data into a central monitoring and control software, which is also used to parameterize the system's components. This integration allows for deriving valuable insights on energy management, which cannot be obtained with regular off-grid systems.

The system includes the following components:

- Photovoltaic module: 400 Wp - 4 kWp
- Small wind power module: 400 Wp - 2.5 kWp
- Fuel cell module: 1200 W
- Battery bank: 100 - 300 Ah
- Electrolyser: 30 - 60 Sl/hour
- Hydrogen storage canister: 1500 - 4500 Sl storage capacity (metal hydride canister)
- Central energy management module
- System controller with monitoring and control software
- Measuring technology (e.g. wind velocity gauge, H2 flow meter)
- Electronic load
- Service

The New Energy Lab from Heliocentris is offered as a turnkey solution. Comprehensive service – from consultation to installation and training of users – is included.

## 4 System Scheme

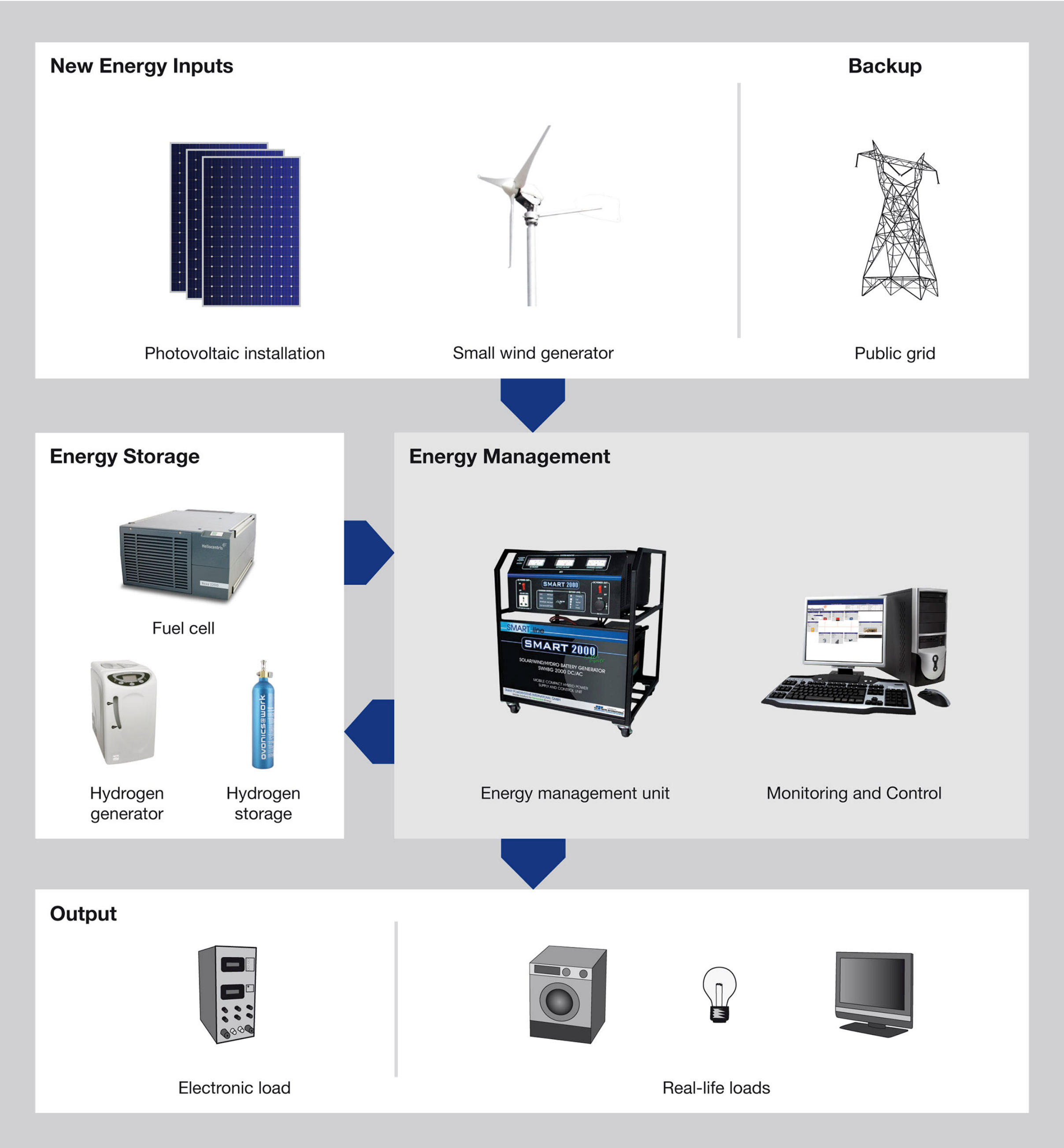



**Figure 1: System scheme.**

## References

[1] M. Meinhardt, M. Wollny, A. Engler. „AC-gekoppelte Inselnetze zur Integration in wachsende Energieversorgungsstrukturen der Zukunft“ (VDI-Berichte, Band 1929)

[2] M. Vetter, G. Bopp, B. Ortiz, S. Schwunk. PV-Hybridsysteme zur Versorgung von technischen Anlagen, Einzelhäusern und Inselnetzen (VDI-Berichte, Band 2058)

[3] B.Fontaine, D.Fraile, M.Latour, S.Lenoir, P.Philbin, D.Thomas. ”Global Market Outlook for Photovoltaics until 2013” (EPIA, April 2009)

[4] K. Rupprecht. „Markteinführung von Brennstoffzellen“ (AiF Brennstoffzellenallianz ZBT Duisburg)

[5] Energy Lab Solution for Bapco, Al-Nakheel at Awali Park. (www.bapco.com.bh)

| | |
|---|---|
| **SM** | **Existing and Emerging Markets** |
| SM.1 | Off-Grid Power Supply and Premium Power Generation |
| SM.2 | Space and Aeronautic Applications |
| SM.3 | APUs for Road Vehicles, Ships and Airplanes |
| SM.4 | Portable Applications and Light Traction |

# Aerospace Applications of Hydrogen and Fuel Cells

Christian Roessler, Joachim Schoemann, and Horst Baier

**Abstract**

The expected climate changes force the aviation industry to reduce emissions. The fuel cell offers high efficiencies and hydrogen, as the fuel of choice, a much higher energetic value than fossil fuels. The requirements for fuel cell systems on flying platforms comprise low weight, high reliability, and insensitivity to temperature and density changes, in addition to high tilt angles. Fuel cell-powered air vehicles are only competitive where low power and high endurance are required. This is the case for small unmanned vehicles, which are already operated with suitable systems in a considerable number. As proven by prototypes based on motor gliders, manned air vehicles can also be powered only by fuel cells, but the flight performance is poor compared with their internal combustion engine equivalents. In the area of transport aircraft, the use of fuel cells as a primary power source is unrealistic. The technology is hence considered for auxiliary power sources or ground power supply. The type chosen for the recently flown and developed vehicles is almost exclusively the proton exchange membrane fuel cell. For applications in transport aircraft, the solid oxide fuel cell is also considered because of its ability for reforming kerosene, which will still be the fuel for the next decade.

# Innovative Hydrogen Storage Solutions for Aerospace Applications

**M. Keding**, **A. Reissner**, **G. Schmid**, **M. Tajmar**, AIT Austrian Institute of Technology GmbH, Austria

Innovative hydrogen storage solutions are increasingly important for a number of future aerospace applications [1]. The Austrian Institute of Technology (AIT) is presently developing an innovative hydrogen storage system based on a combination of high pressure storage in hollow microspheres and chemical hydrogen storage. Our patent-registered system provides a double hydrogen generation process without any external energy or heat during storage or gas release. Analysis shows that such a system can reach hydrogen storage capacities of up to 10 wt% at ambient pressures and temperatures in theory. Gaseous hydrogen was stored in hollow glass microspheres (5 – 200 µm diameters) under high pressure (140 – 700 bar). The sphere-wall is impermeable for hydrogen at ambient temperature; the heating of the spheres increases the diffusion of hydrogen through the wall. Disadvantages of this storage method are the required high heat quantity of the microsphere due to the low thermal conductivity of glass ((0.1 – 0.2 W/(m*K)). The innovative AIT system consists of three stepps [2]. In the first step, water is used as a functional liquid to carry the hollow glass microspheres which are loaded with up to 700 bar of hydrogen gas. NaBH4 were injected together with the glass microspheres into a reaction chamber. There the water reacts catalytically with the $NaBH_4$ producing hydrogen, $NaBO_2$ and heat. This heat was used to release the hydrogen from the hollow glass microspheres. The spheres are coated with a catalyst. Hence most of the $NaBH_4$ is converted at the surface of the spheres due to the catalyst. The heat production has a maximum value at the surface of the spheres which increase the overall efficiency. All end products in this process (empty microspheres and sodium metaborate) are recyclable and can be filled again respectively. The storage capacity depends on the sphere dimensions and the weight of the spheres, the hydrogen pressure and the used hydride. First microsphere filling tests were done during 2 weeks in a high pressure autoclave at 250 °C and 700 bar maximum pressure. Further hydrogen filling tests were done during 1 week at 150 °C and 140 bar. The permeation of hydrogen through the wall depends on the hydrogen diffusivity. It is a function of the temperature, the composition of the sphere material, the wall thickness, the pressure difference and the exchange area. Some previous made heating tests with filled S38 microspheres (350 bar and 700 bar) from 3M™ at different temperatures showed that the released hydrogen was nearly the same due to the fact that the 700 bar microspheres had an age of 100 days and hence approx. half of them were broken during this period. This can be explained with the fact that the S38 spheres have a minimum fractional survival of 80 % at 280 bar. Storage capacities of about 1.9 wt% were achieved at 190 ° after 19 hours. Recent tests with S38 microspheres (filled with 140 bar hydrogen) showed no diffusion process at RT and no broken spheres. This confirmed the assumption, that long-time gas storage in microspheres is possible, if the pressure of the minimum fractional survival rate is higher than the filling pressure. Hence high pressure gas storage up to 700 bar seemed to be possible for example with S60hs or iM30K microspheres. Another important part of the storage system was the coating of microspheres with different catalysts. We coated the microspheres with two different catalysts based on rhodium and platinum and two different methods – a wet chemical sol gel process and a sputtering process. The different coating technologies results in different coating properties. The sol-gel coated microspheres have no consistent coating layer in contrast to the sputtered microspheres. Furthermore some spheres were backed or were broken during the process. Only a couple of spheres were broken during the sputtering process. Sputtering seemed to be an applicable process for microsphere coating. The sol-gel method is not suitable due to the fact that the coating is not firmly connected with the microspheres and could be washed down from the spheres. The sputtered microspheres showed good reaction rates in combination with sodium borohydride injection. During the tests an uncommon thermal behavior was observed. The temperature inside the chamber reaches it maximum after a few seconds without microspheres at a heating test. Uncoated microspheres reach its maximum temperature after a few minutes due to their very low thermal conductivity. The maximum temperature is 35% lower due to the additional mass of microspheres. The coated spheres should show the same behavior, but the maximum temperature is only 40% of the uncoated microspheres. Furthermore the temperature reaches its maximum after a few seconds. Both results can be explained with a significantly higher thermal conductivity of coated microspheres versus uncoated microspheres, in spite of the very low coating layer thickness of about 4 nm. The experiments were done with platinum sputtered microspheres, whereas the thermal conductivity of copper is more than 5 times higher for example. Further tests have to be done to verify our results. This includes tests with higher pressure (350 bar and 700 bar) and long-time gas release tests. Furthermore additional tests will be done with helium instead of hydrogen to demonstrate the possible use of microspheres as innovative helium storage system. The diffusion mechanisms and the diffusivity of helium and hydrogen are similar but at different temperatures. The required lower temperatures for helium could be realized via an electrical heating unit, if the thermal conductivity of microspheres could be increased significantly by sputtering. Applications for hydrogen filled microspheres were identified in the area of hydrogen generation on satellites, additives for cryogenic fuels, radiation safety and biogas upgrading. Helium filled microspheres could be used to replace high pressure tanks on telecom satellites. The figure shows uncoated (left) and copper sputtered microspheres (right).

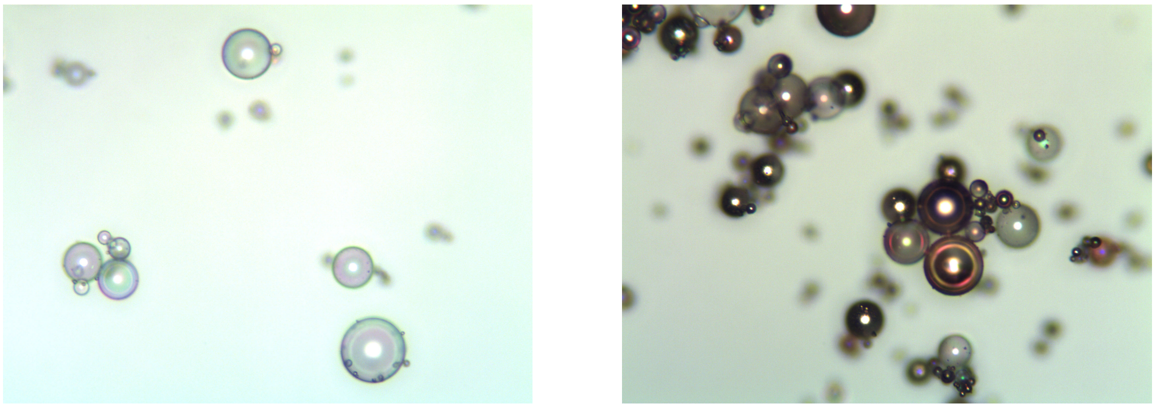


**Figure 1: Picture of uncoated (left) and copper coated (right) microspheres.**

Another project deals with new energy storage solutions to replace APU's or secondary batteries on satellites or aircrafts [3]. We decided to approach this topic by combining a fuel cell with innovative chemical hydrogen and oxygen storage as well as integrating the oxygen storage system into a form that can be used as a structural element. This advantage would be very interesting in order to obtain higher weight efficiencies. Another advantage is the direct integration of the fuel cell into the hydrogen storage material. Thus the power dissipation of the fuel cell can be used for desorption of hydrogen where heat is required, instead of being rejected by a heavy thermal control system. In this project, gaseous hydrogen was stored in a metal hydride (MH). Sodium alanate seemed to be particularly suitable for reversible hydrogen storage on satellites due to its high storage capacities at relatively moderate temperatures and pressures as well as the fact that it is commercially available and lots of kinetic measurement data is available. Sodium alanate is a crystalline complex hydride with tetragonal form. It is colourless and highly sensitive against hydrolysis. It reacts in a three step dehydrogenation reaction and can release 7.4 wt% of hydrogen. The first step is the conversion of $NaAlH_4$ to $Na_3AlH_6$ under aluminium and hydrogen separation. The second step is the conversion of $Na_3AlH_6$ to NaH under aluminium and again hydrogen separation, and the third step is the conversion of NaH to Na under hydrogen separation. However NaH is a highly stable composition and requires high temperatures for separation (approximately 400 °C) which is not acceptable for technical use. A limitation of the process to the first two steps decreases the hydrogen capacity to 5.55 wt%, but also reduces the desorption temperature to less than 150 °C. In order to derive an optimal tank structure, as well as predict the thermal characteristics of any future MH system design, the physical processes during the hydrogen storage and release have been implemented into a coupled fluid/thermal finite elements model using ANSYS™ integrated programming language APDL. A well established model has been applied for the reaction kinetics of absorption and desorption processes of hydrogen containing the four physical processes of chemical sorption, surface transition, diffusion and phase transition. Each of these processes runs at a rate determined by time-dependent parameters. The overall absorption speed of $H_2$ is determined by the minimum taken over the four processes listed above. For desorption, the process is limited by the maximum. Hence it is necessary to simulate all four processes, and calculate the extremal values at each time step. In addition thermal conduction and forced convection by a cooling fluid were taken into account. With a first demonstrator prototype, ca. 500 litre $H_2$ could be stored into 1 kg of sodium alanate which represents a gravimetric density of more than 4 % [4]. The temperature distribution corresponds to the results of the simulation, which verifies the simulation as well as the reactor (so called cheese-) concept forming very homogenous temperatures within the tank. Finally all these test results triggered our interest in developing a hydrogen storage tank based on metal hydrides to replace high pressure tanks in regenerative fuel cell systems (RFCS). The biggest advantage in comparison with high pressure tanks is the possible use of metal hydrides as heat storage system as shown in Figure 2. The main advantage of using a MH in the RFCS is that the power dissipation of the FC (>60% of the generated electrical power, depending on the RFC efficiency) can be used for desorption of Hydrogen where heat is required, instead of being rejected by a heavy thermal control system. The heat is stored in the MH and can be rejected during the loading cycle. Thus, thermal peak loads, for example during energy provision on a telecom satellite, can be avoided completely.

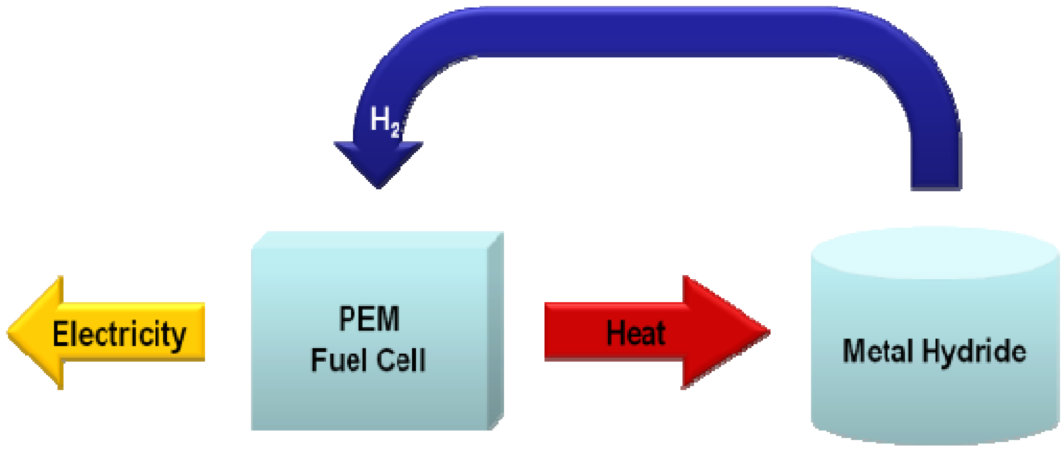



**Figure 2: Heat storage during energy provision.**

Terrestrial fuel cells take the oxygen from ambient atmosphere; hence they do not require oxygen storage tanks. Space applications require oxygen storage, which is usually realized with pressurized gas tanks or solid gas generators. The reversibility of both solutions is difficult, e.g. the compression of gas into a tank requires a large and heavy compressor. We are currently developing a novel reversible oxygen storage solution based on $YBaCo_4O_7$ [5]. The temperature of oxygen as well as $YBaCo_4O_7$ must be at least 350 °C for the absorption of oxygen. Furthermore the medium should be completely surrounded by an oxygen atmosphere. The absorption/desorption behaviour has been measured with a special thermo gravimetric analysis. Such analysis determines changes in weight in relation to change in temperature. The expected rise of weight for the compound is approximately 3 wt%, which equals the absorbed mass of oxygen. The achieved storage effect for the first tests was approx. 35 % of the maximum storage capacity. This could be explained by different particle size distribution, a non-uniform air flow through the material and different pressures inside the reactor. Further tests have to be done to optimize the material and the measurement system. Based on these results, we will simulate and design the overall reversible oxygen tank system.

## References

[1] A. Züttel et al., Hydrogen as Future Energy Carrier (2008), Wiley-VCH Weinheim, Germany

[2] M. Keding et al., Innovative Hydrogen Storage in Hollow Glass-Microspheres, Hydrogen and Fuel Cells Conference 2009, Vancouver/British Columbia

[3] A. Strand et al., Regenerative Fuel Cell Systems for Satellites, 8th European Space Power Conference 2008, Konstanz, Germany

[4] M. Keding et al., Development of a Ti-doped Sodium Alanate Hydrogen Storage System, Hydrogen and Fuel Cells Conference 2009, Vancouver/British Columbia

[5] M. Karppinen et al., Oxygen Nonstoichiometry in $YBaCo_4O_{7+\delta}$: Large Low-Temperature Oxygen Absorption/Desorption Capability, Chemistry of Materials Vol. 18: 490-494, 2006

# Desulfurization of Jet Fuel for Fuel Cell-based APU Systems in Aircraft

**Y. Wang**, **J. Pasel**, **R. Peters**, **D. Stolten**, Forschungszentrum Jülich GmbH, Jülich, Germany

**Summary**

To prevent the catalysts in fuel cell systems from poisoning by sulfur containing substances the fuel to be used must be desulfurized to a maximum of 10 ppmw of sulfur. Since the conventional hydrodesulfurization process employed in the refinery industry is not suitable for mobile fuel cell applications (e.g. auxiliary power units, APUs), the present study aims at developing an alternative process and determining its technical feasibility. A large number of processes were assessed with respect to their application in fuel cell APUs. The results revealed that a two-step process combining pervaporation and adsorption is a suitable process for the on-board desulfurization of jet fuel. The investigations to evaluate this process are presented in this paper. Seven different membrane materials and ten sorbent materials were screened to choose the most suitable candidates. Further laboratory experiments were conducted to optimize the operating conditions and to collect data for a pilot plant design. Different jet fuel qualities with up to 1650 ppmw of sulfur can be desulfurized to a level of 10 ppmw.

## 1 Introduction

Fuel cells are well suited for on-board power supply in aircraft, ships and heavy duty vehicles. The use of fuel cell systems in aircraft offers the possibility to simplify the aircraft layout. Important systems in aircraft, i.e. the gas turbine powered auxiliary power unit (APU) for electricity supply, the fuel tank inerting system and the water tank, can be substituted by one single system, the fuel cell system. The waste heat of the fuel cell system can be used for ice protection. These measures reduce the consumption of jet fuel, increase aircraft efficiency and allow operation with low emissions. Additionally, the costs for aircraft related investments, for aircraft maintenance and operation can be reduced. APUs driven by conventional gas turbines operate at an efficiency of about 15% on the ground [1], while an APU based on autothermal reforming of diesel or gasoline in combination with a Polymer Electrolyte Fuel Cell (PEFC) can achieve a system efficiency of up to 36–37% [2, 3].

To operate fuel cells with the fuel available on board, the fuel is converted into a hydrogen-rich gas by a process of catalytic reforming. Since both the catalysts in the reformer and in the fuel cell can be deactivated by the sulfur compounds contained in the fuel, the liquid fuel must be desulfurized to a level with a maximum of 10 ppmw (parts per million by weight) of sulfur [4, 5, 6]. Whereas diesel fuel for road vehicles within the EU is already desulfurized at the refinery, jet fuel is permitted to have up to 3000 ppmw of sulfur worldwide [7, 8]. An analysis of fuel samples showed that jet fuel with a total sulfur content ranging from 300 ppmw to 700 ppmw has been marketed in Europe. On-board desulfurization is therefore required for the use of fuel cell auxiliary power units (APUs) in aircraft.

## 2 Process Design

In the petroleum industry, low-sulfur fuels are often obtained by hydrocracking processes or hydrotreating processes, so-called hydrodesulfurization (HDS). However, this conventional method is highly inconvenient for reducing sulfur compounds to the desired level in a mobile fuel cell system with a capacity range of 5-10 kW, since improvements of the hydrodesulfurization efficiency are limited by increasingly severe operating conditions and escalating costs [9, 10].

Therefore a newly developed desulfurization process is needed for this application. To this end, a large number of processes described in the literature were assessed with respect to their application in fuel cell APUs. A very promising approach combining a pervaporation and adsorption process is presented in this paper. The simplified process flow is shown schematically in Figure 1.

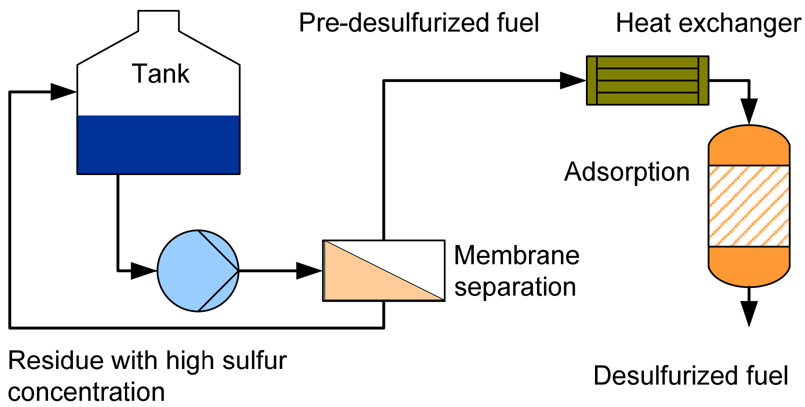



**Figure 1: Process flow sheet of combined pervaporation and adsorptive desulfurization.**

In this approach, the liquid fuel is first heated to the desired temperature and then fed into the membrane section in which the pervaporation is applied to reduce the sulfur content to relatively low levels. Subsequently, the pre-desulfurized liquid fuel is further treated by an integrated fixed-bed adsorption, while the residue with enriched sulfur content is channeled back to the aircraft's fuel tank.

Desulfurization by pervaporation is a process that extracts aromatics from aliphatic hydrocarbons by solvent diffusion transport through a non-porous membrane. Partial vaporization occurs as a result of vacuum, while the membrane acts as a sulfur-selective barrier between the two phases: the liquid phase retentate and the vapor phase permeate. The sulfur molecules can be pulled through the membrane and concentrated at the permeate stream if aromatics preferentially diffuse through the polymer. The other concept is to use a membrane which enriches the sulfur content in the retentate side by the opposite effect [11, 12, 13].

Desulfurization by adsorption is a technology which uses a solid adsorbent to selectively adsorb organosulfur compounds from refinery fuel streams. Adsorptive desulfurization only employs physical adsorption in which organosulfur compounds stay on the solid sorbent surface in the original form. Regeneration of the sorbent is done by flushing the spent adsorbent with a desorbent resulting in a highly concentrated organosulfur compound flow. The adsorption process is performed under mild conditions and no $H_2$ is consumed. It is anticipated that sulfur can be removed to the ultraclean level of 10 ppmw or even lower [9, 10].

## 3 Pervaporation Experiments

The pervaporation experiments were conducted on a lab scale. In the present study, the permeation flux $J_P$ is calculated by weighting the permeate relative to the outer surface of the membrane. The separation factor is determined as $\beta = (C_s)_{Per} / (C_s)_{Feed}$ . It denotes the ratio between the weight fraction of sulfur components recovered in the permeate and the weight fraction of sulfur components entering the process. The measured separation factors along with the corresponding permeate flux for six different membranes are shown in Figure 2.

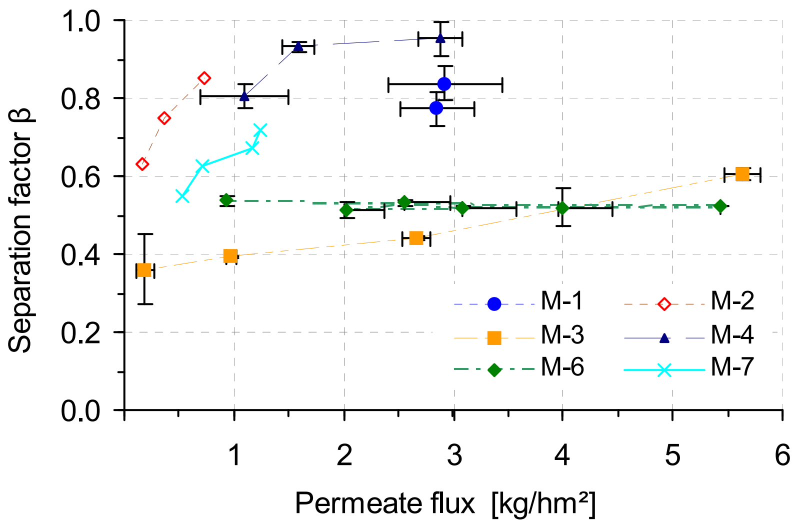



**Figure 2: Membrane screening using Jet A-1 with 564 ppmw S for M-1, M-2 and M-3; Jet A-1 with 712 ppmw S for M-4, M-6 and M-7 with operating conditions as: feed temperature $T_{feed}$: 70 – 140 °C, feed flow rate $\dot{V}_{feed}$: 300 – 720 ml/min, permeate temperature $T_{per}$: -196 °C, and permeate pressure $p_{per}$: 1 – 50 mbar (results with 95% confidence intervals).**

The best pervaporation behavior is obtained with the polyurethane membrane M-3 for treating Jet A-1 with 564 ppmw S. Depending on the operating conditions, a separation factor from 0.40 to 0.60 can be achieved with a corresponding permeate flux of 1.00 kg $h^{-1}$ $m^{-2}$ to 5.64 kg $h^{-1}$ $m^{-2}$. However, the pervaporation performance with membrane M-3 was instable and a drastic degradation effect was even observed after a certain experimental period. Additionally, membrane M-6 is also considered to be a promising candidate. The separation factor amounts to approximately 0.52 with permeate fluxes of 0.93 – 5.40 kg $h^{-1}$ $m^{-2}$ for treating Jet A-1 with 712 ppmw S. Therefore, membrane M-6 was selected for further analysis in permeation experiments because of its relatively stable and promising pervaporation performance.

A series of experiments with kerosene (1650 ppmw S) were carried out based on the statistical experiment design. The experimental results can be presented here as the following graphic plots which are accomplished with the software STAVEX 5.1 from company AICOS (Figure 3).

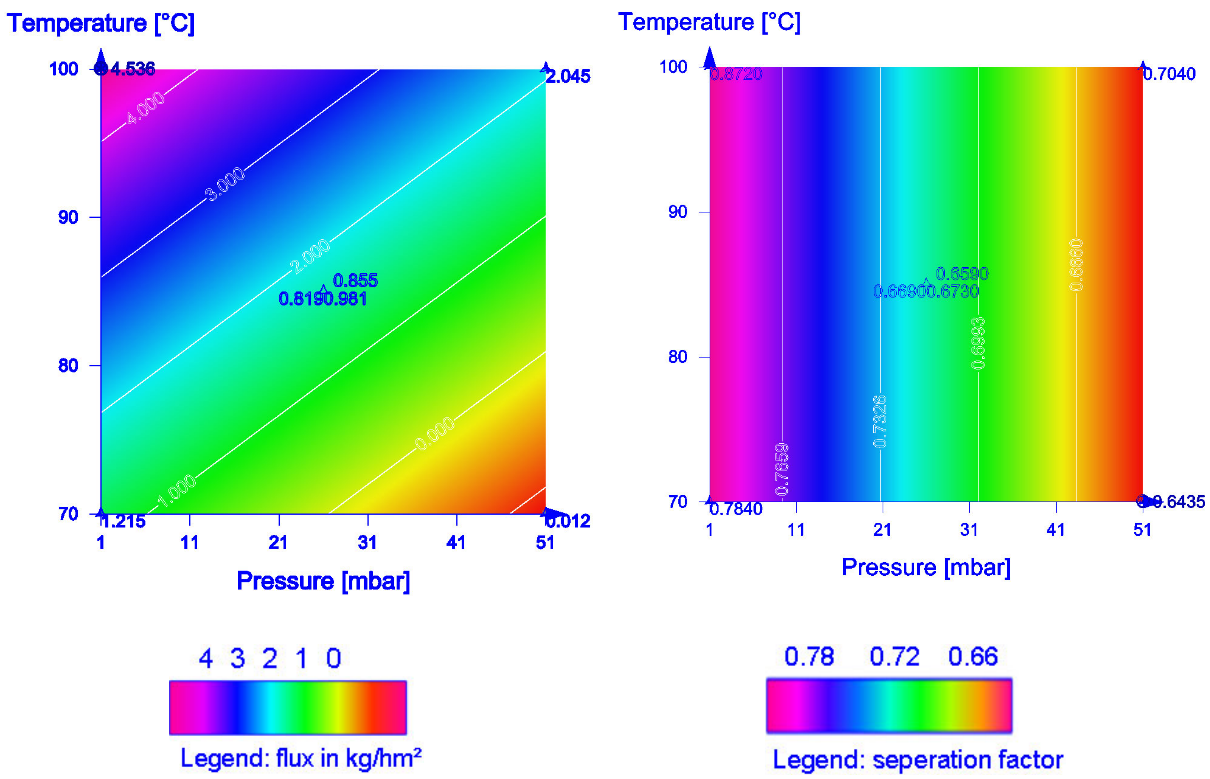



**Figure 3: Results of statistical analysis in regard to the permeate flux $J_P$ and the separation factor β in the ranges studied 70 °C < $T_{feed}$ < 100 °C and 1 mbar < $p_{per}$ < 51 mbar; membrane M-6 with kerosene 1650 ppmw S; permeate temperature $T_{Per}$: -11 °C.**

In the ranges studied for membrane M-6, i.e. 70 °C < $T_{feed}$ < 100 °C and 1 mbar < $p_{per}$ < 51 mbar, the feed temperature ($T_{feed}$)and the permeate pressure ($p_{per}$) have a significant influence on the permeate flux and the separation factor. It can be seen that large separation factors and high permeate fluxes using membrane M-6 were obtained at low permeate pressures and high feed temperatures. Therefore, it is not possible to determine optimal operating conditions which lead to a low separation factor and a high permeate flux coincidentally. Considering the energy demand in an industrial application the economical operating conditions are determined here as a feed temperature of 90 °C and a permeate pressure of 25 mbar. Under these conditions a separation factor of 0.71 and a corresponding permeate flux of 2.26 kg $h^{-1}$ $m^{-2}$ were attained.

A different separation property was observed in the pervaporation of a light fraction of Jet A-1 with 290 ppmw S through the polyimide membrane M-5. At a permeate pressure of 4 mbar and a feed temperature of 134 °C a separation factor of 3.08 was achieved through membrane M-5 with 50% light cut of Jet A-1 provided by thermal distillation. The corresponding permeate flux was 0.38 kg $h^{-1}$ $m^{-2}$. This permeation potential provides another possibility for removing sulfur components by producing a retentate that has a lower sulfur content. Furthermore, in an industrial application a multi-stage membrane separation process is very attractive. The first step can be achieved by a polyurethane membrane with a sulfur reduction on the permeate side. Then the low sulfur fraction is fed to the subsequent step, in which a polyimide membrane with the opposite pervaporation behavior is employed to enrich the sulfur content on the permeate side. Future efforts on the second pervaporation step will firstly aim at screening more polyimide membranes and optimizing their pervaporation performance.

## 4 Adsorption Experiments

The low sulfur permeate fraction obtained with pervaporation experiments was supposed to be desulfurized subsequently by adsorption. However, since only a limited amount of permeate was collected from the permeation test rig, diverse light fractions of Jet A-1 produced by distillation were employed as analog permeate fractions. Analyses revealed that the substantial composition of both fractions is comparable.

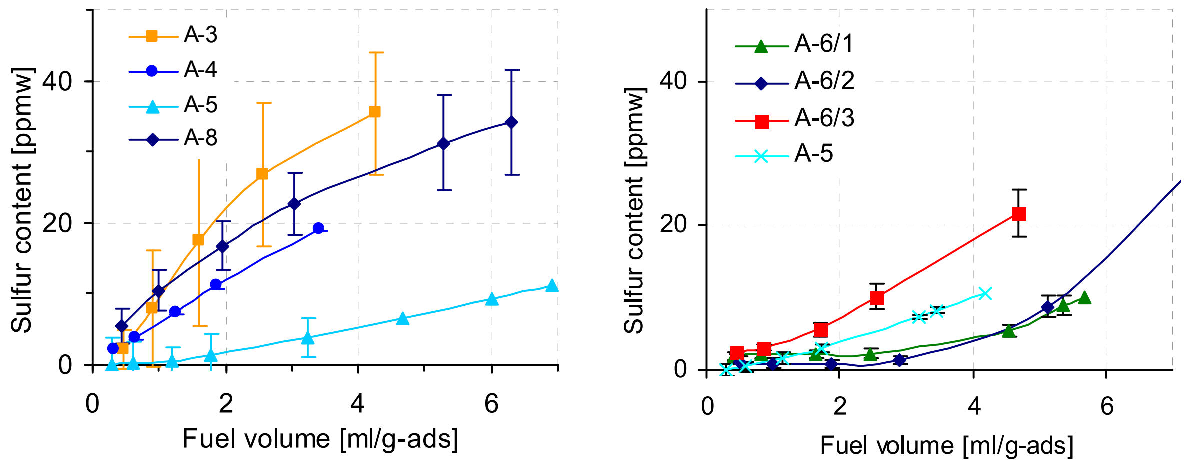



**Figure 4: Adsorbent screening with 50% (vol.) light fractions of Jet A-1 (left: 290 ppmw S; right: 440 ppmw S); adsorption temperature $T_{ads}$: 20 – 140 °C; LHSV*: 1 $h^{-1}$; regeneration temperature $T_{reg}$: 500 °C; heating time t: 3 h and GHSV*: 655 $h^{-1}$; cumulative breakthrough curves obtained with consecutive desulfurization cycles (results with 95% confidence intervals).**

A regeneration process with subsequent adsorption is denoted as an adsorptive desulfurization cycle. Multiple cycles were carried out consecutively to prove the reproducibility of the experiments. Figure 4 demonstrates the adsorption behavior of the eight most effective adsorbents from our laboratory experiments in operation with two kinds of 50% (vol.) light fraction of Jet A-1 having 290 ppmw and 440 ppmw S, respectively. Corresponding to the cumulative sulfur content of 10 ppmw 1 gram of adsorbent A-3, A-4, A-5, or A-8 is capable of treating 1.05, 1.65, 6.3, or 0.95 ml of 50% (vol.) Jet A-1 with 290 ppmw S, respectively, while 1 gram of adsorbent A-5, A-6/1, A-6/2, or A-6/3 is capable of treating 4.03, 5.68, 5.35, or 2.55 ml of 50% Jet A-1 with 440 ppmw S.

The best breakthrough adsorption capacity $W_s$ of 1.93 mg S/g of adsorbent is obtained with adsorbent A-6/1, while A-3, A-4, A-5, A-6/3, and A-8 offer capacities of 0.23, 0.37, 1.52, 0.89, and 0.21 mg S/g of adsorbent, respectively. The consecutive desulfurization cycles with adsorbent A-6/1 did not exhibit any observable loss in sorbent breakthrough capacity, which is remarkable and is ideal for cyclic processes. Additionally, adsorbent A-6/2 is also considered to be a promising adsorbent with a sulfur capacity of 1.89 mg S/g of adsorbent. Therefore, in designing the adsorption process adsorbent A-6/1 was employed to optimize the operating conditions.

To optimize the adsorption and regeneration behavior, a series of experiments were performed with adsorbent A-6/1 and a 50% (vol.) light fraction of Jet A-1 containing 440 ppmw S on the basis of the statistical experiment design. According to the experimental results the sulfur adsorption capacity $W_s$ and the percentage of sulfur removal in the regeneration process can be expressed as the following graphic plots in the ranges studied (Figure 5):

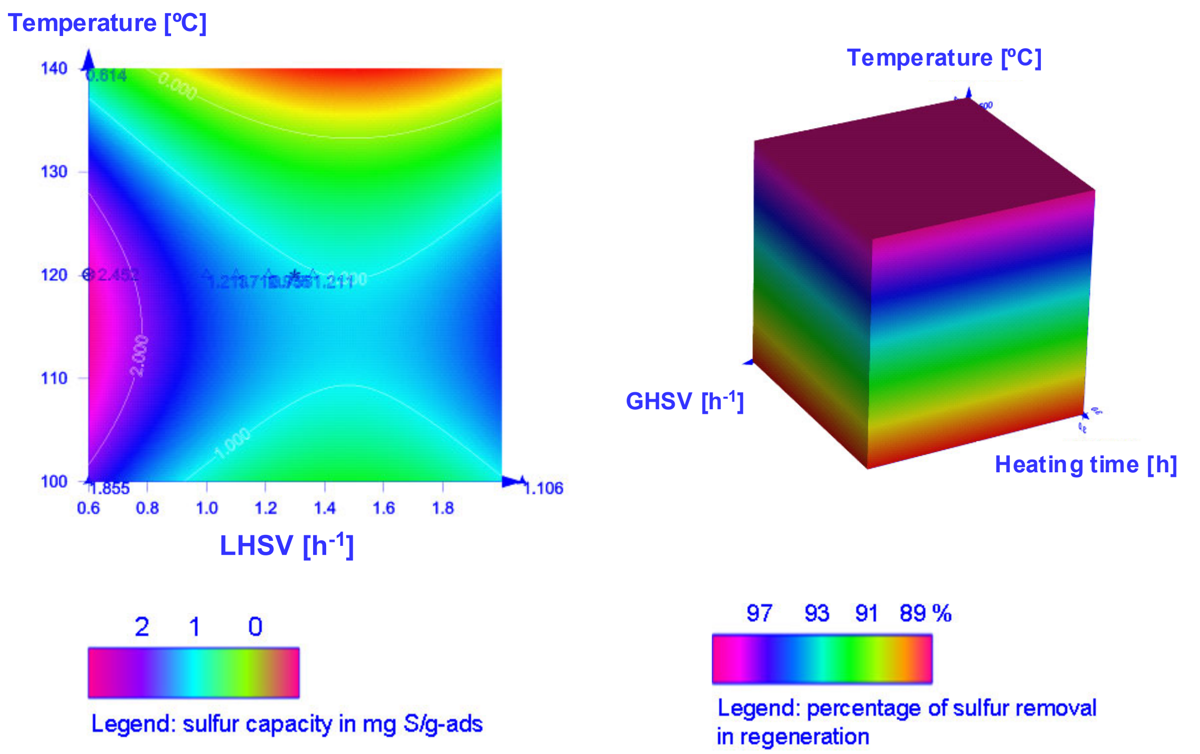



**Figure 5: Results of statistical analysis for adsorbent A-6/1 with 50% light fraction of Jet A-1 having 440 ppmw S; left: influence of adsorption temperature $T_{ads}$ and LHSV on the adsorption capacity $W_s$, 100 °C < $T_{ads}$ < 140 °C, 0.6 $h^{-1}$< LHSV < 1.8 $h^{-1}$, $T_{reg}$ = 500 °C, t = 3 h, GHSV = 655 $h^{-1}$; right: influence of regeneration temperature $T_{reg}$, heating time t and GHSV on the sulfur removal in regeneration process, 400 °C < $T_{reg}$ < 500 °C, 1 h < t < 3 h; 100 $h^{-1}$ < GHSV < 655 $h^{-1}$, $T_{ads}$ = 120 °C, LHSV = 1 $h^{-1}$.**

Both of the adsorption temperature and LHSV influence the adsorption capacity in the range studied, as illustrated in the left graphic in Figure 5. The highest sulfur adsorption capacity of 2.45 mg S/g of adsorbent was obtained with an adsorption temperature of 120 °C and an LHSV of 0.6 $h^{-1}$. Considering the operating conditions in industrial applications, the optimal adsorption temperature and LHSV are determined as 120 °C and 1 $h^{-1}$, respectively.

The graphic cube in Figure 5 demonstrates that the percentage of sulfur removal in the regeneration process ranges from 97% to 100%. The improved sulfur adsorption performance can be achieved by an increase in the regeneration temperature $T_{reg}$, the heating time t and the GHSV of the treatment air. The consecutive desulfurization cycles indicate that the adsorption capacity can be fully recovered by regeneration at 500 °C for 3 hours with GHSV of 655 $h^{-1}$, which is regarded as the optimum regeneration condition.

As an economical alternative, the regeneration process may be accomplished at 450 °C for 2 h with a GHSV of 200 $h^{-1}$ resulting in a 10-20% reduction in the breakthrough adsorption capacity. Since under these conditions, less energy and a smaller amount of regeneration gas are required, this alternative will be chosen for operating conditions in a pilot plant.

## 5 Conclusions

In this study, liquid phase desulfurization of jet fuel by a combined pervaporation and adsorption process was examined. Seven different membrane materials and ten sorbent materials were screened to choose the most suitable candidates. Laboratory experiments were conducted to optimize the operating conditions and to collect data for a pilot plant design. As a result, Kerosene containing 564-1650 ppmw S can be desulfurized by membrane separation with a reduction of up to 50%. Subsequently, the fixed-bed adsorption process with integrated sorbent regeneration is able to reduce the sulfur content in the pre-treated fraction to less than 10 ppmw.

More experiments in regard to multi-membrane separation and multi-bed adsorption will be carried out in the laboratory at IEF-3. As the next step a combined process of pervaporation and adsorption for kerosene desulfurization will be installed as a pilot plant in the 5 kW class.

## References

[1] D. Dagget, J. Freeh, C. Balan, D. Birmingham. Fuel Cell APU for Commercial Aircraft, Proceedings Fuel Cell Seminar, Miami Beach, U.S.A., 2003.

[2] T. Grube, R. Menzer, R.C. Samsun, J. Pasel, R. Peters. Optionen und Herausforderungen des Einsatzes von Auxiliary Power Units in mobilen Anwendungen, VDI-Berichte No. 1975, 2006.

[3] S. Specchia, A. Cutillo, G. Saracco, V. Specchia, Concept study on ATR and SR fuel processors for liquid hydrocarbons, Ind. Eng. Chem. Res. 45 (2006) 5298–5307.

[4] J. Pasel, J. Meißner, Z. Porš, R.C. Samsun, A. Tschauder, R. Peters. Autothermal reforming of commercial Jet A-1 on a 5 $kW_e$ scale, International Journal of Hydrogen Energy, Vol. 32, 2007.

[5] J. Hagen. Technische Katalyse – Eine Einführung, Weinheim, 1996.

[6] W. Benz. Einfluss von Schwefelverbindungen in flüssigen Kohlenwasserstoffen auf ein Brennstoffzellen-Gesamtsystem am Beispiel eines katalytischen Crackers mit nachgeschalteter PEMFC, PhD thesis, University of Duisburg, 2005.

[7] Zehnte Verordnung zur Durchführung des Bundes-Imissionsschutzgesetzes (10. BImSchV) vom 24.6.2004, BGBl. I No. 30 2004, pp. 1342 – 1347.

[8] Ministry of Defence: Defence Standard 91-91; Turbine Fuel, Aviation Kerosine Type, Jet A-1, Nato Code: F-35, Joint Service Designation: AVTUR, Issue 5, United Kingdom of Great Britain and Northern Ireland, 2005.

[9] C. Song. An overview of new approaches to deep desulfurization for ultra-clean gasoline, diesel fuel and jet fuel, Catalysis Today, Vol. 86, 2003.

[10] I.V. Babich, J.A. Moulijn. Science and technology of novel processes for deep desulfurization of oil refinery streams: a review, Fuel, Vol. 82, 2003.

[11] R. Peters, J. Latz, J. Pasel, D. Stolten, Desulfurization of Jet A-1 and heating oil: general aspects and experimental results, ECS Transact. 12 (1) (2008) 543–554.

[12] J. Balko, G. Bourdillon, N. Wynn, Membrane separation for producing ULS gasoline, PTQ Spring (2003) 17–25.

[13] L.S. White, R.F. Wormsbecher, M. Lesemann, Membrane separation for sulfur reduction, Patent: US 2004/0211706 A1 (2004).

# Unmanned Aerial Vehicle Driven by Fuel Cell Technology, AVIZOR

**Esther Chacón**, **Graciano Martínez**, **Carlos Anchuelo**, **Raquel Cuevas**, National Institute for Aerospace Technology, Spain

## 1 Introduction

The National Institute for Aerospace Technology (INTA), is a Public Research Body specialised in aeronautics and space technology R&D, and belongs to the Spanish Ministry of Defence.

Within INTA primary missions are to provide scientific support and technical assistance to the government services and to the industry. In this context, since the early seventies, renewable and alternative energies have been one of the R&D areas in which INTA has dedicated a continuous effort.

From a Spanish strategic point of view, INTA is promoting the use of hydrogen as an energy carrier long-term option, as well as the utilization of fuel cells as very efficient conversion devices for application in transportation and stationary electricity generation.

Apart from R&D activities, INTA is a national centre with testing capabilities accredited on aerodynamics, aerospace structures, automobiles, EMC (Electromagnetic Compatibility), environmental testing, solid rocket motors, space PV cells and turbojet engines. INTA owns and operate premises for unmanned air vehicle (UAV) systems testing.

Since 2003 a programme on the use of fuel cells for defence application was initiated. The first phase of the programme is devoted to develop diesel and ethanol reformers to be integrated with fuel cells and to build a power generation system demonstrator based on fuel cells. In order to test and monitor the technology developments, a test bench for fuel cells is being set up with a capability in electrical power up to 30 kW.

## 2 Fuel Cells for Aeronautic Applications

The National Institute for Aerospace Technology undertook in 1998 the development of vigilance and observation system based on unmanned aerial vehicle (UAV), designated with the name of SIVA. INTA has designed, developed and tested the system and the main subsystems, including the flight control.

SIVA is a sophisticated UAV surveillance system with multiple applications in civil and military fields, and can be used as an observation vehicle in real time. In the first step the vehicles from the SIVA project have been powered by a conventional internal combustion engine and at the moment, the Institute continues to develop new generation unmanned aircraft: mini UAV and micro UAV. After due consideration INTA decided to begin the study of a second phase of this project including fuel cells technologies, in order to evaluate the feasibility to include an electrical engine driven from the power supplied by a PEMFC or a similar system using fuel cells and $H_2$ technologies.

**Figure 1: SIVA UAV.**

Fuel cells are an attractive technology for implementation as power plants for aircraft because of their potential for rechargability and high energy density. The project is in the feasibility phase and the initial configuration envisages the use of compressed hydrogen and PEM fuel cells.

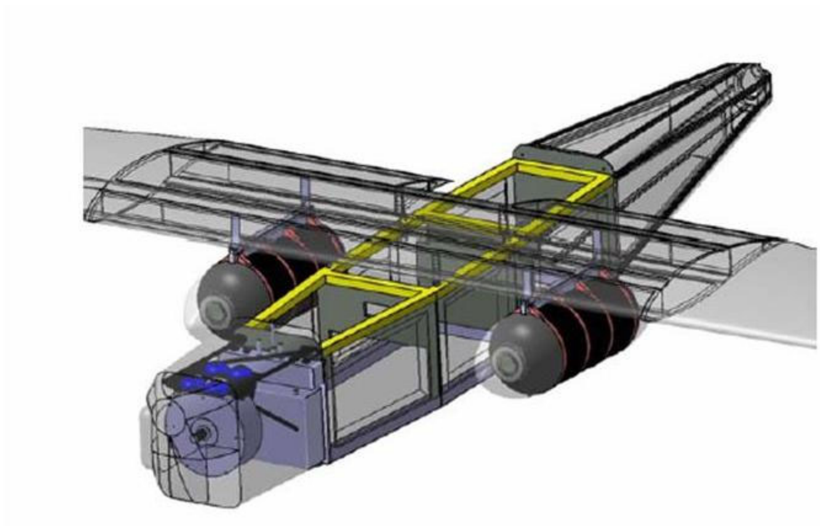


**Figure 2: Plane model.**

The main objective of this project is to prove with a theoretical study and practical tests, the feasibility to include a full UAV system with similar performances like the previous one, but driven by a fuel cell system.

The project base is the model designed and built to SIVA Project. For that reason, the Avizor provide an initials design data belonging to the project previous, and regarding fuel cell PEM, it is detailed below:

The system configuration has been chosen on the base of pre-dimensioning calculations considering several options: using air or pure oxygen as an oxidant, and using a small or big battery pack. The final solution for this project uses pure oxygen at a working pressure of 2 bars.

**Table: System configuration.**

| AERIAL PLATFORM | REQUIRED POWER, during different flight steps: | |
|---|---|---|
| Maximum weight: 300 kg (takeoff) | Takeoff: | 26 kW during 90 s. |
| Wingspan: 5,81 m | Rising: | 20 kW during 30 min |
| Load Factor: 3,5 g (Landing) & 4,4 g | Cruising speed: | 16 kW |
| Range: around 1 hour | Auxiliary systems: | about 1 kW |
| Maximum altitude: 1000 m | | |
| Max. pitch: 21° & Max. roll: 60° | | |

## 3 AVIZOR System

The AVIZOR system is made up of three main parts:

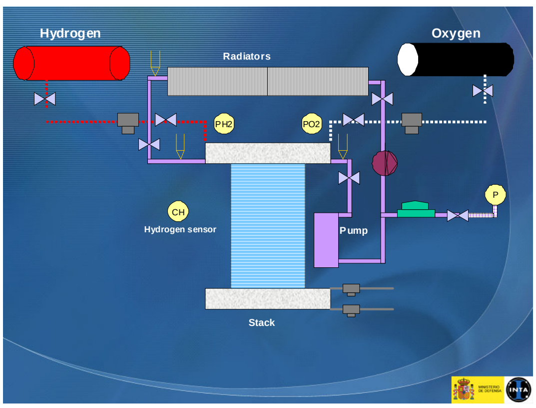
- Power system (Fuel Cell and batteries)
- Engine and controller
- Fuel Storage

The AVIZOR system details are the following:

### 3.1 Power system (fuel cell)

Among the different types of fuel cells, proton-exchange membrane fuel cells (PEMFCs) are considered the best solution for the propulsion system of this application at the moment.

The functional role of the PEFC System (extracted from the functional analysis) is to provide electrical energy to an electrical converter (high voltage) which will provide a voltage compatible with the high and low voltage electrical networks of the plane. System is supplied from fuel and combustive from requirements of the UAV communication network. This system must be cooled to insure optimal operating conditions.




- Stack (One stack between 20 and 30 kW).
- Max. Volume: 46 X 24 x 115 cm [W x H x L], (127 l).
- Cooling system (coolant pump).
- Cathode humidification system.
- Water management system.
- Voltage output 60 – 96 V.

**Figure 3: Stack configuration.**

In order to achieve a fuel cell system appropriate for the UAV project, the components concerning about the preliminary specifications are detailed next:

### 3.2 Power system (auxiliary batteries)

Aim of doing to make a light vehicle and a system more efficiency our first studies recommend to use an auxiliary battery that can supply the additional power for the takeoff and during a few minutes just to the final flight level. We propose to use a modular and rechargeable ion-lithium high power battery.

The batteries of AVIZOR are of nanophosphate lithium-ion. These batteries provide low weight and very fast discharge with high power (as others lithium ion technology) but also very fast charge at high power with a high level of safety.

### 3.3 Engine and controller

The electrical engine that works together with the fuel cell will run in a continuous mode, so it shall be a high efficiency and a long useful life device. For this application we have considered "brushless" engines like appropriate equipment working in a high speed. The electrical engine is according to the industry standard for reliability, functionality and performance in fuel cell test equipment, in the same way it should be compatible as much as possible with INTA techniques and actual laboratory systems. The location into the platform should achieve the best configuration to avoid aerodynamics problems.

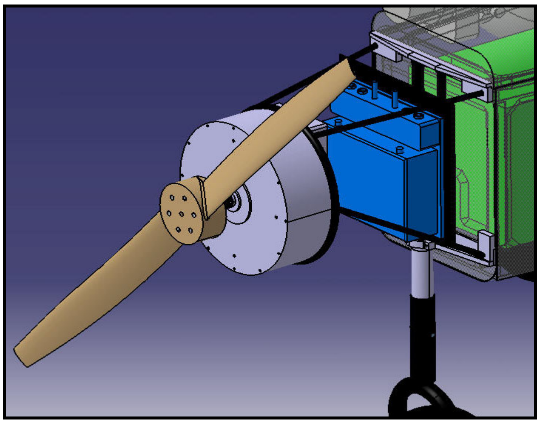


**Figure 4: Engine and controller.**

Brushlees PM Motor:

- Peak power: 47 hp; 35 kW
- Continuous power: 31,5 hp; 23,5 kW
- Maximum speed: 4500 RPM

Controller/Inverter:

- Nominal input range: 270 to 336 VDC
- Input current limitation: 300 A
- Inverter type: PWM & phase advance

### 3.4 Gas storage (hydrogen and oxygen)

After considering different possibilities, (liquid hydrogen, high pressure gaseous hydrogen, metal hydride storage,….etc), we have decided to use in a first step two 25 L wing spot (Pn= 350 ~ 750 bar and 1200 ~ 1600 gr of Hydrogen), with a total weight of around 30 kg. The oxidant is high pressure gaseous oxygen and the storage system is a tank to 200 bar.

- Two tanks around 25 l each.
- Pressure: 350 bar
- Tank Weight: 15 kg each

The use of oxygen instead of air makes it possible to be freed form the humidification of gasses supplying the fuel cell stack. Indeed, in the case of an air supply, oxygen accounts for only 21% of cathodic gas put in contact with the stack. Its flow must thus be almost 5 times higher than in the case of a pure oxygen supply, with for consequence a drying of the stack, moisture being evacuated with nitrogen of the air.

The absence of nitrogen among the combustive gas also allows to an operating process in dead-end mode without recirculation, without risk of smothering of the stack. It consumes the whole anodic and cathodic gas progressively of its need, controlling the gas inputs, and thus frees us from a management of the input of gases and from a recirculation loop on the anodic line, rather complex control.

**References**

[1] International Energy Agency (2006), Energy Technology Perspectives: Scenarios & Strategies to 2050, OECD/IEA, Paris.

[2] International Energy Agency (2005), Prospects for Hydrogen and Fuel Cells, OECD/IEA. Paris

[3] J. Milliken, A.D. Little. “Program Overview Department Transportation Fuel Cell Program” 2000.

[4] James S. Cannon, “Clean Hydrogen Transportation: A market opportunity for Renewable Energy”. REPP Issue Brief Nº 7, April 1997

[5] W.A. Amos, “Costs of Storage and Transporting Hydrogen, NREL 1998.

# Airport Liquid Hydrogen Infrastructure for Aircraft Auxiliary Power Units

**Christoph Stiller**, **Patrick Schmidt**, Ludwig-Bölkow-Systemtechnik GmbH, Germany

## 1 Introduction

The aviation sector is increasingly facing challenges with potentially severe impacts on the business as we know it. Challenges are inter alia reduced availability, more volatile and increasing prices of liquid hydrocarbon fuels, greenhouse gas (GHG) emission regulations, and stricter noise and air pollutant emission regulations especially for on-ground pollution at large airports. While biofuels cannot tackle all these issues, and shifting to hydrogen propulsion appears to be a long-term remedy, hydrogen-powered fuel cell auxiliary power units (APUs) show near-term potential to decrease ground pollution and offer some economic opportunities. In addition to pollution and emission-free power supply and air conditioning while on ground, these APUs can also be operated while airborne to produce power, facilitating efficiency improvements and weight reductions at the main engines since generators can be avoided. Co-products of the fuel cell system can be used aboard, e.g. water for air humidification and sanitary system, and the oxygen-lean exhaust air for inertisation of the fuel tanks [1].

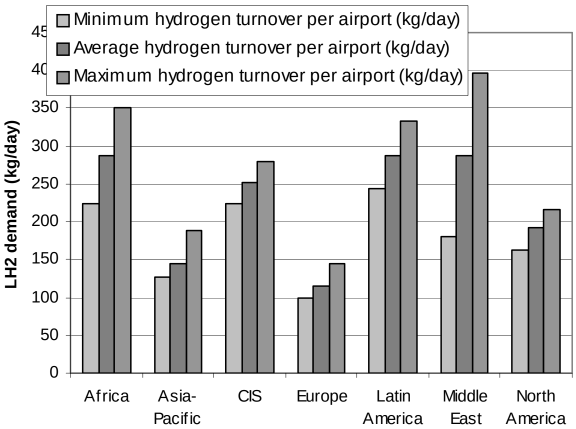
For the on-board supply of the APUs, liquid hydrogen ($LH_2$) is advantageous due to its high energy density and low hazard potential. A study was recently performed for aviation industry assessing the required ground infrastructure to supply aircraft APUs with liquid hydrogen. A build-up scenario of hydrogen demand at worldwide airports was established, and the most likely hydrogen supply options for different demand categories were elaborated. Potential 'killer criteria' along the supply chain were assessed and synergies between $LH_2$ supply to aircraft APU and other hydrogen applications inside or outside airports considered. This paper will highlight main results of the study.

Comparative environmental and cost performance of kerosene, hydrogen, and alternative fuels for use in aircraft APU have also been studied, but are not part of this paper.

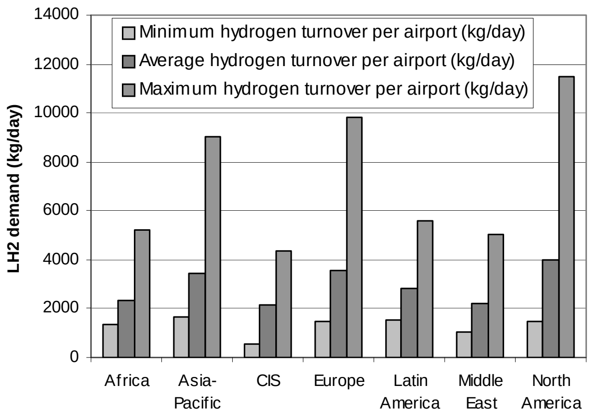
## 2 Quantity Structure of Airport $LH_2$ Demand

A tentative quantity structure for hydrogen demand at airports was established for two penetrations of fuel cell APU aircrafts (50 / 6,500 short range aircraft with fuel cell APU in operation worldwide). To calculate the airport-specific demand, the largest airports in terms of passenger throughput in 2006 were identified per world region, and the $LH_2$ demand was scaled according to the number of passengers. Provided that aircraft $LH_2$ refuelling can be carried out once a day (with some flexibility) within the regular turnaround times, it was found that only a small number of airports worldwide would need to be equipped with $LH_2$ infrastructure for both penetration scenarios (~20 airports to supply 50 aircraft; ~130 airports to supply 6,500 aircraft). Assuming that an aircraft with fuel cell APU consumes about 70 kg

$LH_2$ per day, liquid hydrogen demand at the specific airports would amount to 100 – 400 kg/day for the 50 aircraft case, and 1 – 12 t/day for the 6,500 aircraft case (see Figure 1). In case refuelling is more time consuming and can only be done during night time, more airports will need to offer hydrogen and the average airport $LH_2$ demand per airport will be lower, leading to substantially higher costs. However, we expect the refuelling procedure to be quick enough to be done between two missions.




50 FC APU aircraft (total)




6,500 FC APU aircraft (total)

**Figure 1: Quantity structure for airport $LH_2$ demand.**

## 3 Options to Supply Aircraft APU with Liquid Hydrogen

Figure 2 shows options to supply liquid hydrogen to airports, along with potentials for usage of hydrogen at and around airports. Hydrogen is produced and used on a large scale in industry today and further demand increase is expected for the near future. Assuming that $LH_2$ APUs are the only consumers at an airport, for dedicated production at the airport forecourt, only hydrogen production methods suitable for small scale (i.e. electrolysis, steam methane reforming, and biomass gasification) are applicable. The in this case inevitable forecourt liquefaction is, however, only efficient enough if the daily $LH_2$ demand exceeds ~1 ton. In addition, central large-scale hydrogen production, liquefaction, and transport to the airport will be an option, where trailer trucks are the most flexible and suitable means of transporting $LH_2$ both land-side and at the apron, while ship and railway transport are suitable for longer distances and larger volumes. Pipeline transport of gaseous hydrogen is only viable in case of large volumes and shorter transport distances, or as part of a pipeline grid. In this case, liquefaction facilities are required at the airport forecourt.

To deliver $LH_2$ to the aircraft, apron tanker trucks, apron ring pipelines and exchangeable cartridges can be imagined. Because of the rather low volumes of hydrogen consumed by APUs, $LH_2$ pipelines will not be advantageous due to the high evaporation losses caused by heat entry. Cartridges will imply high investments for infrastructure (filling, exchange system) and be technologically more challenging onboard than a fixed tank, piping and a refuelling nozzle. Refuelling of an aircraft $LH_2$ tank by trucks is therefore seen as the most promising option. Experiences gained and technologies developed for refuelling cars with $LH_2$ tank, such as with the BMW Hydrogen 7, can be useful for an aircraft $LH_2$ refuelling system.

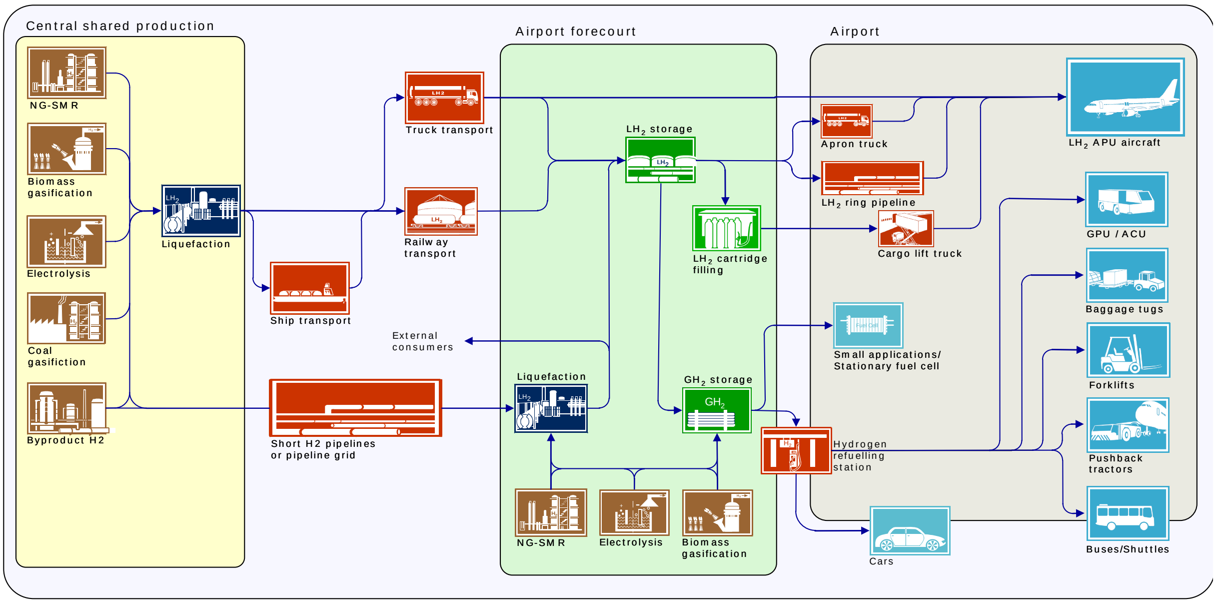



**Figure 2: Options for supply of airports with $LH_2$ and usage.**

If the supplying hydrogen liquefier is less than 200 km away from the airport and the airport $LH_2$ demand is below ~2.3 t/day[1], a single combined tank and refuelling truck would be sufficient to refuel the aircraft during daytime and drive to the liquefier to be refilled during night time (so-called “one-truck-solution”). This is believed to be a very interesting option especially for the early phase with very low hydrogen demand, because beside the truck practically no additional infrastructure is required. For higher demands and longer distances, several trucks and possibly a stationary liquid hydrogen tank will be required.

[1] Assuming an average of 2 refuellings per hour, 16 hours operation, and 70 kg per refuelling

## 4 Availability of Liquid Hydrogen and Airports for Early Adoption

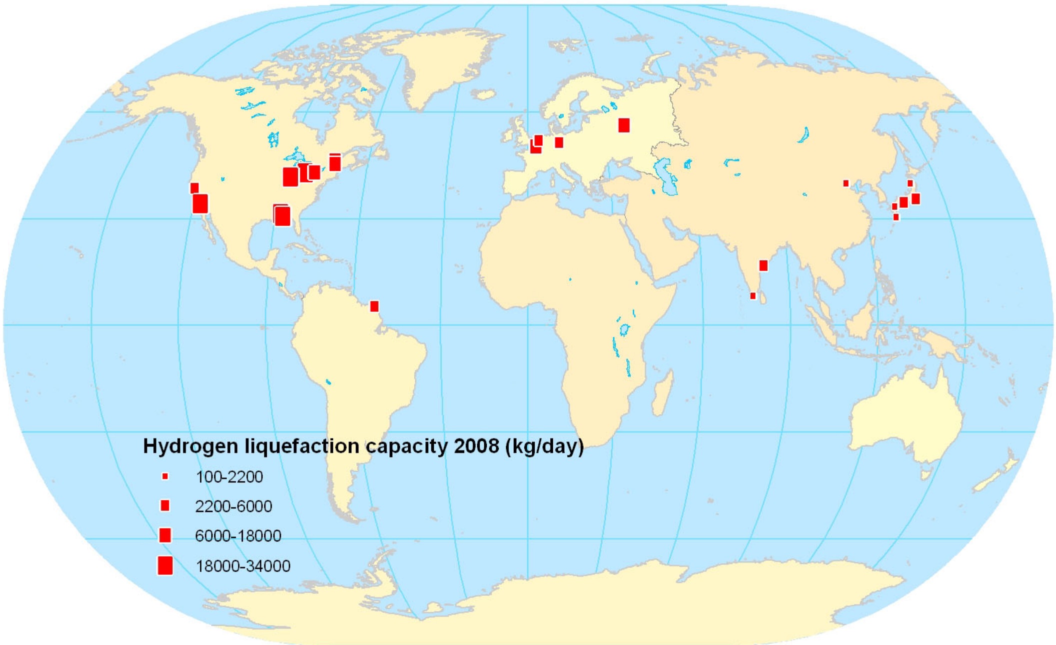



**Figure 3: Map of existing hydrogen liquefiers (state: December 2008).**

An option for some airports during the early phase of low hydrogen demand is to build on existing production and liquefaction capacity. Out of various sources [2, 3, 4], the total worldwide liquefaction capacity of the year 2008 has been estimated and the results can be seen in Figure 3. The global capacity for $LH_2$ is ~120,000 t/year (i.e. only about 0.1% of all hydrogen consumed). Most liquefiers are operated in North America, Japan and Europe. For comparison: 50 short-range aircraft with fuel cell APU would require app. 1,300 t (1.1% of the overall capacity), and 6,500 aircraft would require 166,000 t/year (1.4 times the overall capacity). Depending on the capacity utilisation of the existing liquefiers, a number between 50 and 500 aircraft APUs can probably be supplied without installing new liquefaction capacity.

With regard to the above introduced “one-truck-solution”, especially airports where the next liquefier with free capacity is close appear most promising as a starting point. Furthermore, due to higher flexibility in logistics planning and public visibility, it is assumed that large airports are best suited as early adopters of this technology. A ranking of international airports was done based on their number of departures 2006 (data from [5]) and their distance to the next liquefier[2]. It can be seen that due to size and vicinity to liquefiers, a number of airports in the USA (Chicago, Los Angeles, Ontario) and Japan (Tokyo, Osaka) have favourable conditions to provide liquid hydrogen for aircraft APUs, and furthermore

---

[2] A score was calculated based on the departures in 2006, and multiplied with a factor of three, if the next liquefier is less than 20 km away (linear distance – road distances might be some 20-40% more), and a factor of two if the distance is less than 50 km. Airports above 100 km distance were excluded.

Beijing, Toronto and Amsterdam airports could be hubs for such aircraft. Provided that the liquefiers have sufficient capacity available, this offers initiation of $LH_2$ supply at very limited investment. Since the aircrafts need to be refuelled with $LH_2$ only once a day, one stop per day at one of the hubs is theoretically sufficient; in between, also other airports can be approached.

**Table 1: Ranking of airports according to departures and distance to next liquefier.**

| Rank | Airport name | City | Country | Departures 2006 | Linear distance next liquefier (km) |
|---|---|---|---|---|---|
| 1 | CHICAGO OHARE INTERNATIONAL | CHICAGO | USA | 479322 | 51 |
| 2 | CAPITAL | BEIJING | CHINA | 188322 | 38 |
| 3 | LOS ANGELES INTERNATIONAL | LOS ANGELES | USA | 328421 | 89 |
| 4 | TOKYO INTERNATIONAL | TOKYO | JAPAN | 162026 | 26 |
| 5 | CHICAGO MIDWAY INTERNATIONAL | CHICAGO | USA | 149274 | 28 |
| 6 | SCHIPHOL | AMSTERDAM | NETHERLANDS | 220077 | 60 |
| 7 | LESTER B PEARSON INTERNATIONAL | TORONTO | CANADA | 208961 | 84 |
| 8 | ONTARIO INTERNATIONAL | ONTARIO | USA | 68131 | 7 |
| 9 | OSAKA INTERNATIONAL | OSAKA | JAPAN | 65413 | 7 |
| 10 | NARITA INTERNATIONAL | TOKYO | JAPAN | 95063 | 39 |

## 5 Possible Killer Criteria and Synergies

Potential killer criteria for the application of aircraft with $LH_2$-powered fuel cell APU were evaluated. From a technological perspective, general killer criteria could not be detected. However, at specific airports the large distance to the next liquefier and limited forecourt site space could be obstacles to a cost-efficient supply of these airports. Remedies include erecting hydrogen plants near the airport or at other airports, or waiting with the hydrogen deployment at these airports until the hydrogen turnover in aviation has increased. For apron distribution and refuelling, venting of larger quantities of boil-off hydrogen should be prevented, which appears to be technically possible.

Rather than on the technical side, potential barriers could appear on the economic side. This technology can only enter the market with investors committed to foster market commercialisation despite low revenues in the early phases and the usual risks of new technology ventures. Also, acceptance by the public and involved players could bear a risk. Since air travel safety tends to be an issue of public concern, airlines may fear rejection by their customers and thus hesitate to employ the new technology. Further, airport operators may face a conflict of interests, since $LH_2$ APUs with flexible refuelling patterns would make aircraft independent of supply of ground power and preconditioned air, which are a source of airport income.

Synergies with other hydrogen applications were assessed. From existing and near-term planned hydrogen demonstration projects at airports, the main synergy effect that can be expected in conjunction with $LH_2$ infrastructure for APUs is the build-up of expertise on handling hydrogen, approval questions, and supplier contracts, which will facilitate a quicker start for the $LH_2$ infrastructure at these airports.

Hydrogen fuelled ground support equipment and vehicles, small applications inside the airport, and airport-bound land-side traffic (e.g. buses, taxis, etc. refuelling primarily at the airport) will increase the overall hydrogen demand at the airport, and hence cause economy of scale effects (see Figure 2). The effect will be largest for land-side traffic, which has a potential hydrogen demand in the same order of magnitude as the APUs. For the APU infrastructure this might lead to cost reductions through common procurement of equipment, enabling an earlier shift to forecourt production, and utilisation of the boil-off of liquid hydrogen applications. Also for the other applications, the hydrogen supply costs will in most cases be lower than if they were the sole consumers of hydrogen at the airport (even if they might prefer gaseous instead of liquid hydrogen then). Since aircraft APUs are the only applications that rely exclusively on hydrogen in liquid state, these synergies can only be secured if the APU players are early out to make the case for an $LH_2$ supply solution (with evaporation step for vehicles with pressure storage). If at first a gaseous supply for other applications is established, the synergy potential from joint procurement is void.

The future use of hydrogen in the road transportation sector is expected to have a significantly higher hydrogen demand than projected for aircraft APUs. This will lead to a better availability of hydrogen, higher density of supply, and hence shorter delivery distances. Further cost reductions will come from market pricing and competition in an upturning market, larger scales for common production and liquefaction, and reduction of component costs (e.g. electrolysis, fuel cells). Also public acceptance will increase with a successful introduction of hydrogen in road traffic. In turn, the hydrogen mobility sector could benefit from aircraft APU applications through an increased availability of $LH_2$ which is a suitable supply vector for e.g. remote areas.

## 6 Conclusions

Overall, our study showed that supplying aircraft APUs with liquid hydrogen appears technologically feasible and, if suitable airports are chosen for early adoption, only moderate equipment and investment is required. Up to a certain penetration level, most airports will be able to rely on $LH_2$ from existing liquefaction capacity. Later, when new capacity is required, this can be shared with other applications and possibly even located on-site the airport.

In addition to risks inherent to novel technologies, potential barriers rather relate to economic interests and strategies of the players. Synergies can be expected from sharing the infrastructure with other large-scale applications such as hydrogen fuelled ground support equipment, apron vehicles, as well as airport-bound vehicles.

Consequently, with any next steps taken, it is recommended to ensure that all required players are sharing the vision, possibly co-ordinate and align infrastructure deployments, and are jointly working for public acceptance of hydrogen in (air) transportation.

**References**

[1] Julika Bleil. Neue Energiesysteme für zukünftige Flugzeuge. Diploma thesis, Hamburg University of Technology. 2006

[2] Website http://www.the-innovation-group.com/ChemProfiles/Hydrogen.htm

[3] Google Map on worldwide liquid hydrogen production,

[4] http://maps.google.com/maps/ms?msa=0&msid=103435144233894559621.0004495596ef3faffc1e2

[5] Roads2HyCom EC project, website http://www.ika.rwth-aachen.de/r2h/index.php/Underground_Hydrogen_Storage_in_Refuelling_Stations

[6] Airports Council International. Updated World Airport Traffic Report 2006. July 2007. Geneva, Switzerland

## SM Existing and Emerging Markets

SM.1 Off-Grid Power Supply and Premium Power Generation

SM.2 Space and Aeronautic Applications

SM.3 APUs for Road Vehicles, Ships and Airplanes

SM.4 Portable Applications and Light Traction

# Auxiliary Power Units for Light-Duty Vehicles, Trucks, Ships, and Airplanes

Ralf Peters

**Abstract**

The demand on electricity in mobile applications increases in nearly all future prospects. Reasons for such a development are electric devices for more comfort and a guaranteed energy supply during idling mode. Today combustion engines and turbo jet engines were applied as auxiliary power units (APU) on-board of trucks and air planes. Fuel cells are envisaged as an environmental friendly and high efficient energy conversion system for future systems. Usually for logistical reasons, APUs must use the same fuel as the main engine. This will be kerosene or JET A-1for air planes and diesel for trucks and ships. This contribution will show the requirements of different applications and will give an overview about today‘s developments.

# Fuel Cell System Development and Testing for Aircraft Applications

**Josef Kallo**, **Gwénaëlle Renouard-Vallet**, **Martin Saballus**, **Gerrit Schmithals**, **Johannes Schirmer**, **K. Andreas Friedrich**, Institut für Technische Thermodynamik, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Stuttgart, Germany

## 1 Introduction

For several years the Institute of Technical Thermodynamics of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) in Stuttgart and Hamburg work actively for the development of fuel cell systems for aircraft applications. In cooperation with Airbus several fuel cell applications within the aircraft for both ground and cruise operation could be identified. In consequence, fuel cell systems capable to support or even replace existing systems have been derived. In this context, the provision of inert gas for the jet fuel (kerosene) tank and electrical cabin power supply including water regeneration represent the most promising application fields.

This contribution will present the state of development and the evolution discussing the following points:

- Experimental evaluation of fuel cell systems under relevant conditions (low-pressure, vibrations, reformate operation, etc.).
- Fuel cell test in DLR’s research aircraft ATRA (A320) including the test of an emergency system based on hydrogen and oxygen with 20 kW of electrical power. The fuel cell system was integrated into an A320 aircraft and tested up to a flight altitude of 25 000 feet under several acceleration and inclination conditions.
- Fuel cell tests in Antares-H2 – new DLR’s flying test bed

## 2 The Multifunctional Concept for Fuel Cell Systems in Aviation: A Step by Step Approach

### 2.1 Power generation

Fuel Cell systems can reach 50 % of electrical efficiency and advantageous replace power supply systems [1-2]. Indeed, one of the main deficits of the current power supply systems in aircraft if that they are often operating in an inefficient way (sometimes high energy consuming). As example, the auxiliary power unit (APU) has a low efficiency of only 20 % and even lower [3] at part load conditions.

Another system not fully efficient in nowadays civil aircraft is an emergency power system the Ram Air Turbine (RAT), which generates electricity from the air stream (essentially the RAT is a propeller). In case all main engines fail (which is a very rare event) the hydraulic system and the electric system of the aircraft are lost.

During cruise the electrical energy is provided by the generators of the main engines. The efficiency of this energy supply is quite high around 30 – 40 %.

The primary goal of fuel cell systems in aircraft is to avoid inefficient operation phases of aircrafts. In this respect, it is envisioned to eliminate the APU and the RAT. An important milestone in the development efforts has been the first tests of a fuel cell in a civil aircraft environment through a collaboration of Airbus, DLR and Michelin to power the aircraft's electric motor pump and the back-up hydraulic circuit and also operated the aircraft's ailerons. During the test, the hydrogen and oxygen based fuel cell system generated up to 20 kW of electricity in flight within the DLR’s D-ATRA ("Advanced Testing and Research Aircraft") [4]. This system was integrated into the cargo area of the A320 at the Airbus location in Hamburg/Germany and tested in several flights with standardized missions. In 2007 and 2008. The data acquisition of the fuel cell system performance was measured under realistic vibration loads, heat rejection and safety aspects. The flight specific data measured includes temperature, pressure, vibrations, orientation angles, etc. The fuel cell system demonstrated a robust behavior in all tests so far (see figure 1).


(a) (b)

**Figure 1: (a): DLR research aircraft A320 (D-ATRA) at Berlin International Air Show (ILA) 2008. (b): Michelin fuel cell system in the cargo area of the research aircraft.**

On top of that power supply, fuel cell systems can also deliver further functions and products like water and low-oxygen containing exhaust air for inerting the jet fuel tank. Another function may be the use the heat of the fuel cells for de-icing. Figure 2 displays schematically the functions that a multifunctional fuel cell system may be able to satisfy.

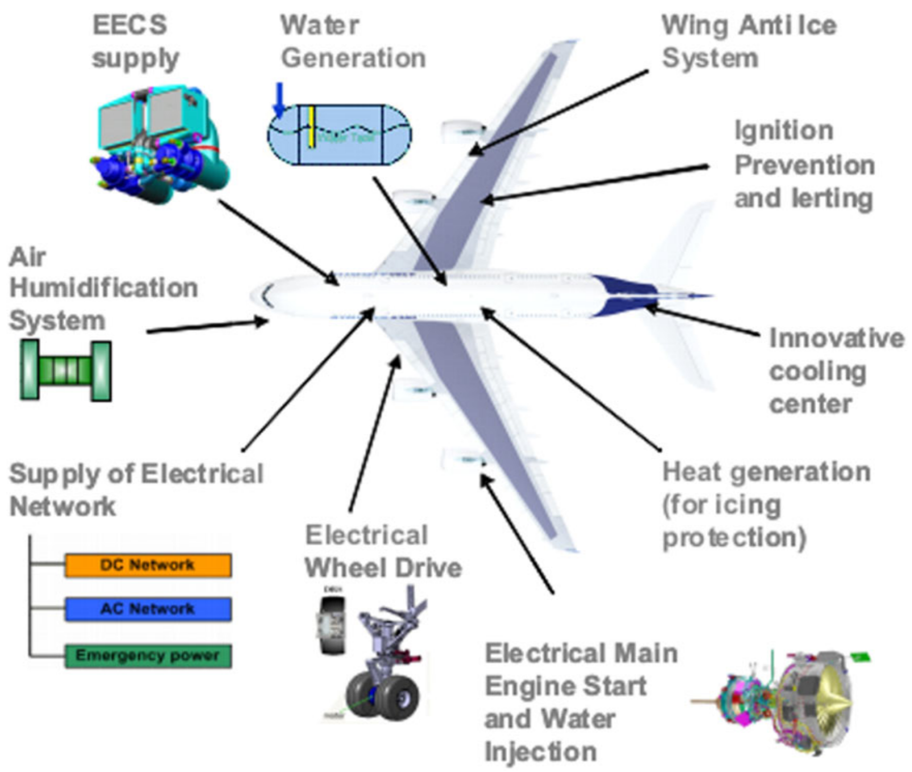
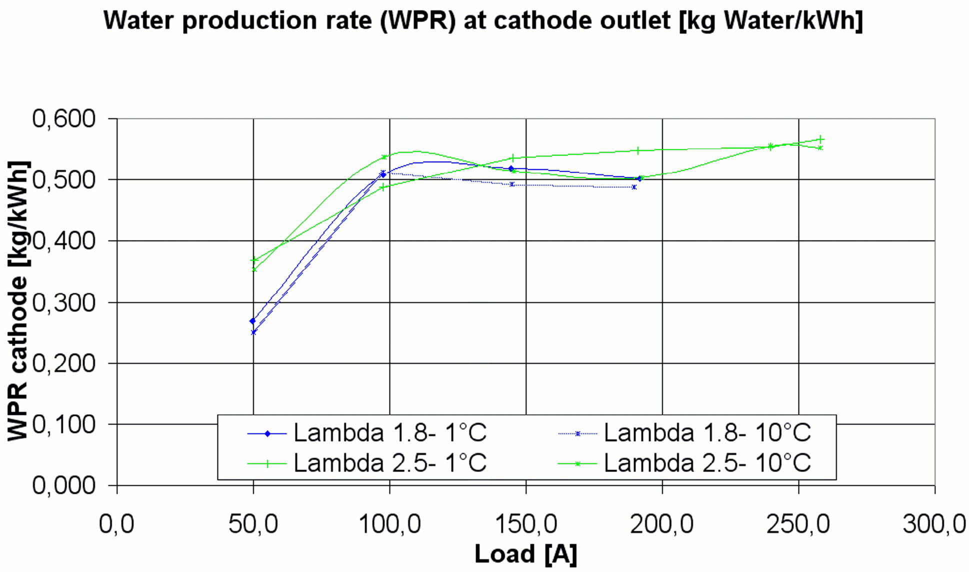



**Figure 2: Multifunctional fuel cell system: The possible functions are power supply, emission free ground operation, electrical main engine start, electrical environmental control system (EECS), water generation (potable water and water for toilets), heat generation (icing prevention, hot water generation), explosion and fire prevention and suppression (inerting of tanks, cargo and e-bay compartment), cockpit and / or cabin air humidification.**

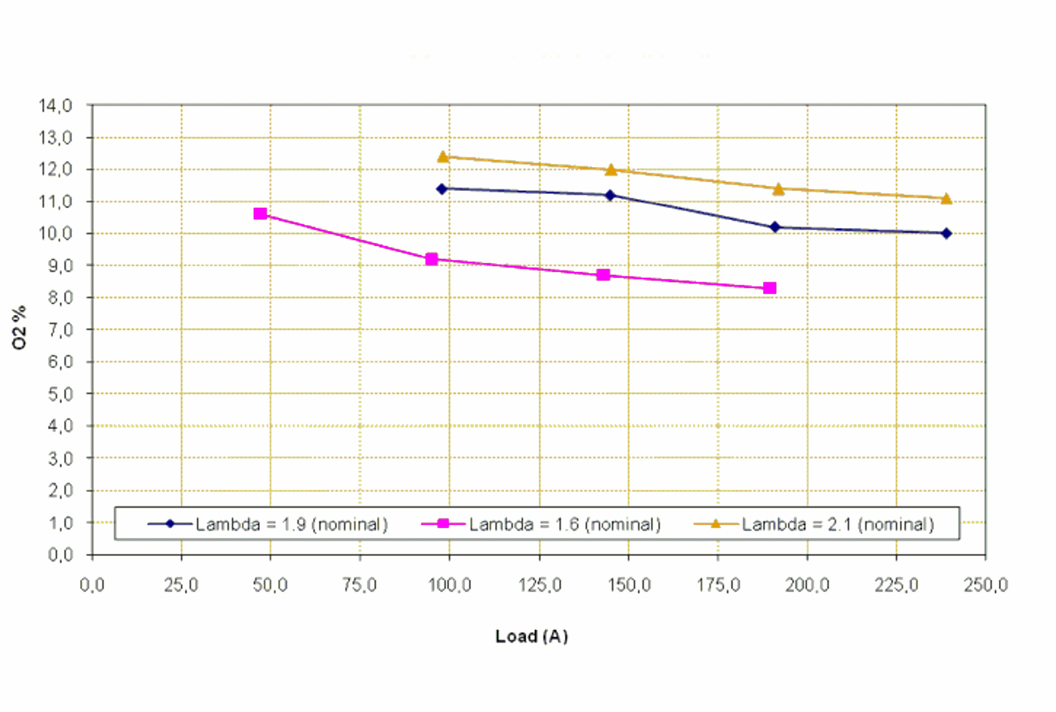
## 3 Water Generation and Inert Gas Generation

Fuel cell system can deliver ca. 0.5 - 0.6 liter of water per kWhr electrical power (see figure 3 (a)); which means that for 100 kW fuel cell power (appropriate for large aircraft) about 50 liter of water are generated per hour. This can be used for toilets and air conditioning thereby reducing the amount of water to be loaded on-board of the aircraft. Therefore water generation by the fuel cell will help reduce the water tank of the aircraft.

Very innovative is the use of the fuel cell exhaust which is oxygen depleted air. Test of various fuel cell systems have shown only 10 % of oxygen content in the exhaust (see figure 3 (b)).These low oxygen contents in the kerosene tank are effective as fire retardation and suppression or explosion prevention.




(a)

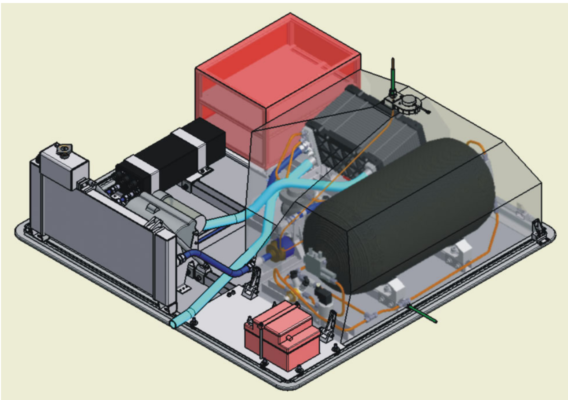



(b)

**Figure 3: (a) Water production rate for a PEFC for different operating conditions and different temperatures of condensation (b) Variation of oxygen content in a PEM fuel cell exhaust depending on operating parameters.**

## 4 The Multifunctional Fuel Cell System: A Path towards Aircraft Integration

A $H_2$/Air fuel cell system being set-up at DLR will demonstrate multiple functions on-board. Besides emergency power, the system should deliver inert gas for the jet fuel tank and water, on ground the system can power an electrical drive on the nose wheel for ground taxiing. The fuel cell system is based on commercial systems which are modified and adapted to fulfill the rules and regulation of aircrafts. A flexible aircraft qualified platform is being developed in which different components can be changed rapidly without the need to start all qualification routines again. With this airworthy test platform the development of aircraft fuel cell can be drastically accelerated. The schematic of this platform is presented in figure 4a. The electrical drive is presented in figure 4b.



(a)

(b)

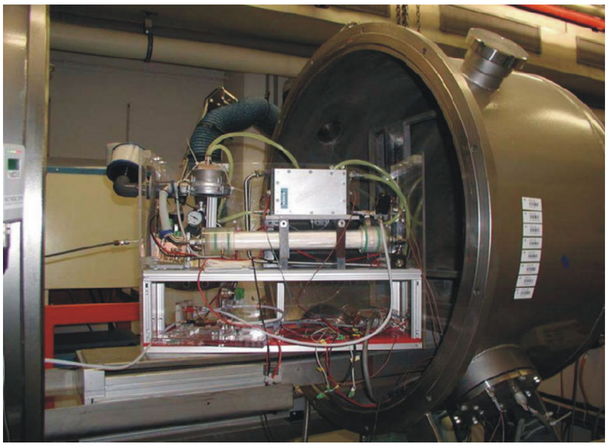
**Figure 4: (a): design of the airworthy (aircraft qualified) testing platform for fuel cell systems. (b): components for the electrical nose wheel drive for emission-free ground operation.**

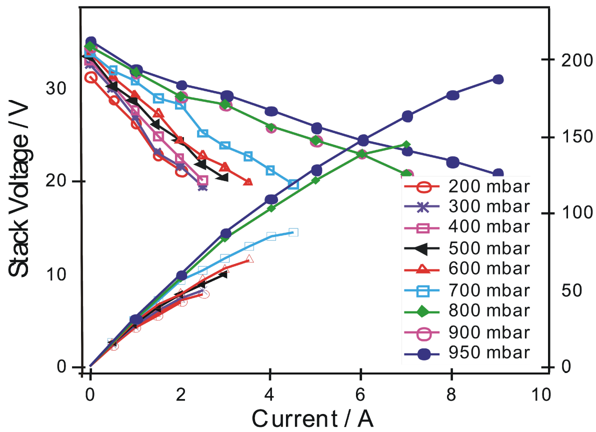
## 5 Aircraft Relevant Investigations

### 5.1 Tests in laboratory environment

Different test environments have been set up to test cells and systems under aircraft relevant conditions in the laboratory.

A specific test is the low pressure operation test down to 200 mbar which corresponds to a flight height of ca. 12 000 meter (ca. 39 000 feet) (figure 5).



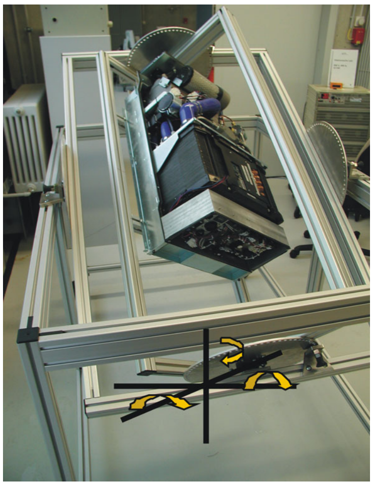


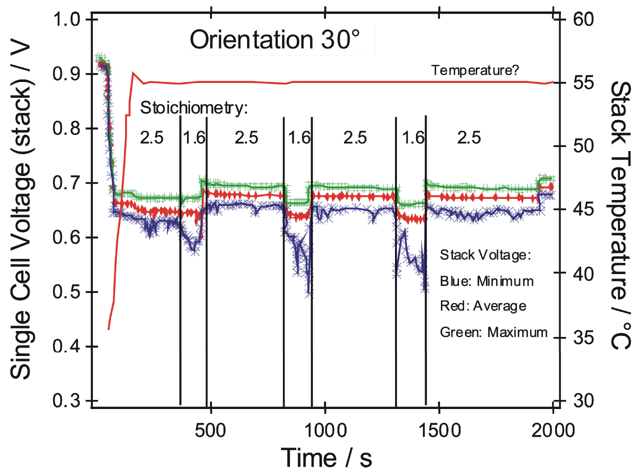

(a) (b)

**Figure 5: (a): photo of a test set-up for analyzing low-pressure behavior of PEFC systems. (b): example of the pressure dependence of a 300 W PEFC system in the pressure range from 950 to 200 mbar.**

Even if the final fuel cell system probably will be operated with cabin air, such characterizations are of paramount importance for system evaluations. The testing results which also include different orientations, vibrational load behavior, electromagnetic compatibility and water analysis, allow designing a layout of the system regarding its performance during cruise conditions.

Another specific test is the different orientations tests(inclinations) of the systems to identify adverse angles. An example is given in figure 6 were the system shows a decrease of cell voltage at an angle of 30° (adverse operating condition). This performance instability is due to the water management of the system. With a change in the system configuration this problem can be effectively avoided.

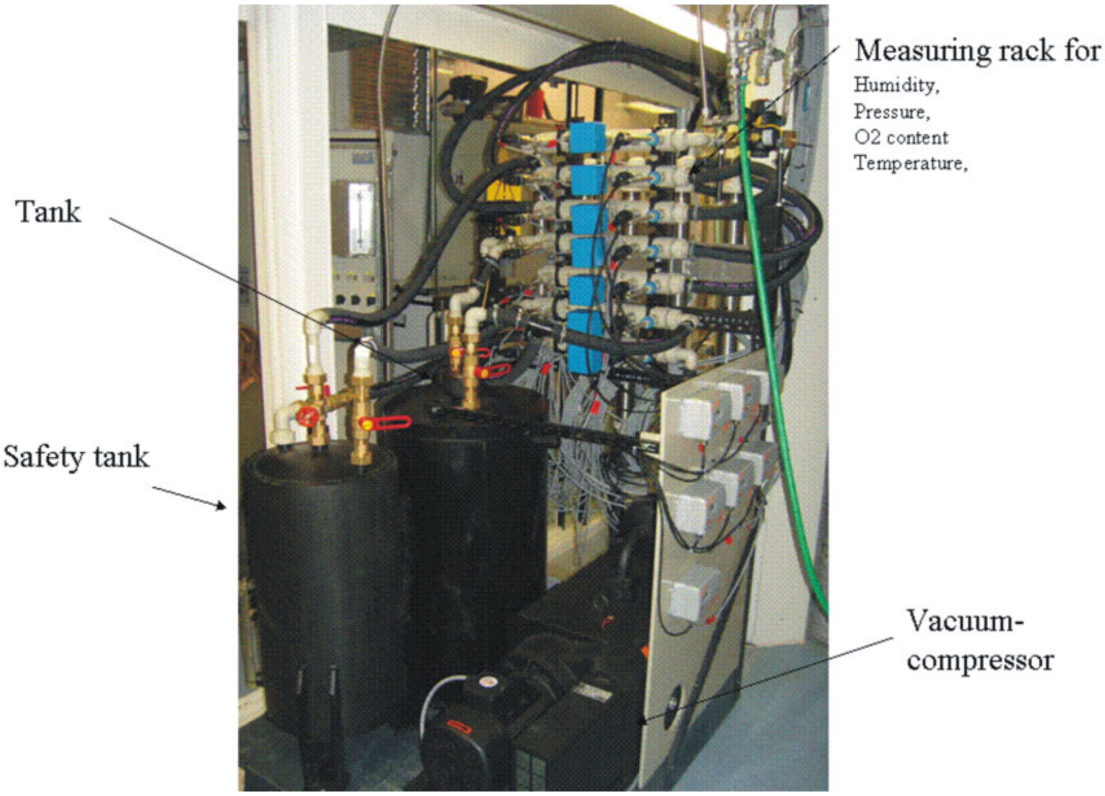





(a) (b)

**Figure 6: (a): inclination test station. (b): testing results of a 12.5 kW system under different orientations. At low air stoichiometries of 1.6 the voltage decreases at 30° angles.**

(a)




(b)

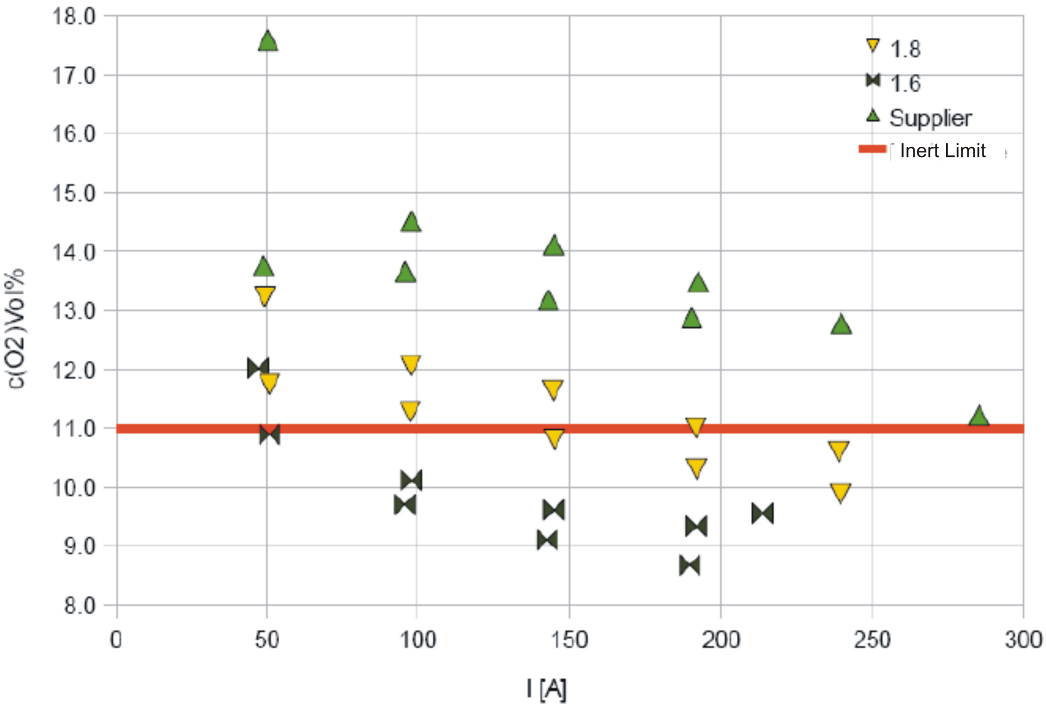



**Figure 7: (a) test bed measurement station. (b): typical test results of $O_2$ concentration measurement n.**

Another test set-up (figure 7) allows experimenting the different possibilities of conditioning the fuel cell cathode exhaust gas in order to optimize the produce water and condition the inert gas before its distribution in the kerosene tank simulating a pressure change in the system representative of the one expected in flight.

## 6 Flight Testing and Development of New Testing Beds

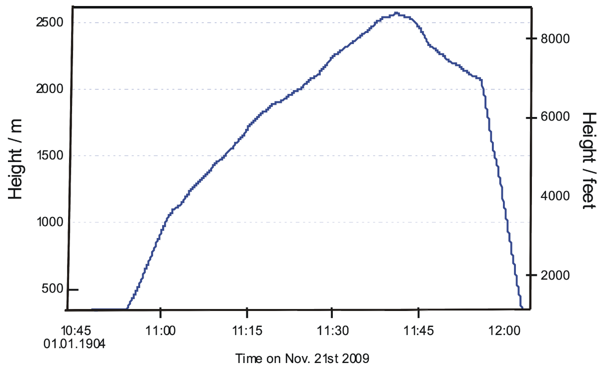
A new testing bed have been developed by DLR in cooperation with Lange Aviation (figure 8): The Antares DLR-H2 is a high-tech motor glider aircraft based on the Antares 20E which has been built commercially and modified by attaching two pods below the wings to carry one the fuel cell system and one the hydrogen tanks [5]. This new test bed allows the combination of different qualifying test routines. Acceleration loads, vibration loads and climatic environments.


(a)

| Geometry | |
|---|---|
| Wing Span | 20 m / 65.6 ft |
| Wing Area | 12.6 m$^2$ / 135 ft$^2$ |
| Aspect Ratio | 31.7 |
| Fuselage Length | 7.40 m / 24.3 ft |
| Fuselage Height | 1.64 m / 5.4 ft |
| **Weight** | |
| Empty Weight | 460 kg / 1014 lb |
| Maximum Weight | 660 kg / 1455 lb |
| Waterballast | 100 l / 26.4 USgal |
| Min. Wing Loading * | 42 kg/m$^2$ / 8.6 lb/ft$^2$ |
| Max. Wing Loading | 52.4 kg/m$^2$ / 10.7 lb/ft$^2$ |
| **Glide Performance** | |
| Best Glide Ratio | 56 |
| Min. Sink Rate at weight | 0.49 m/s / 96 ft/min \| 530 kg / 1168 lb |
| Stall Speed at weight | 73 km/h / 39.4 kt \| 530 kg / 1146 lb |

(c)

(b)




(d)

**Figure 8: (a): testing bed DLR-H2 for fuel cell propulsion with hydrogen. (b): specifications of the Antares motor glider from Lange Aviation. (c): view of the hydrogen tank in the pod. (d) View of the altitude record.**

The Antares DLR-H2 first officially took off on July 7th, 2009 at Hamburg airport. It is the world's first piloted aircraft capable of taking off using only power from fuel cells. On November 21st of 2009, Antares successfully completed an altitude record reaching about 8368 feet (ca 2550 m) in height what correspond to an operating pressure for the fuel cell of about 725 millibars [6] equivalent to the minimum air pressure in the cabin of an Airbus A320 flight during a normal flight and is about 290 millibars below the normal atmospheric pressure.

## 7 Outlook and Summary

A strategic cooperation between Airbus and DLR has resulted in the first results for development of fuel cell systems for future aircraft. The multifunctional approach to fuel cell systems may lead to further modifications in various aircraft systems for efficient energy use on board. The goal of Airbus and DLR is to conceive innovative electrical architectures in which the multifunctional fuel cell system is a key component to ascertain a technology leadership for efficient future aircrafts.

DLR has demonstrated together with Airbus and Michelin the first fuel cell system for emergency power on an A320. An airworthy test platform for flexible investigations of the multiple function and application is being developed. This platform will be used for flight test and rapid change of components. The platform will be tested in-flight in the A320. Furthermore arising from the need to perform tests in the realistic environment the testing bed DLR-H2 will be used intensively within the next few years.

**Acknowledgement**

The development presented is a team effort. The authors are grateful to the Fuel Cell team of Airbus and the team of Michelin for their contribution. and the authors acknowledge the contributions of Michael Schier (electric drives), Christoph Fischer, Gerhard Schuller, Oliver Thalau (flight qualification and platform), Till Kaz, Forian Gores (Antares DLR-H2), Winfried Göbel (low pressure studies), and Jonathan Wicker (inclination tests). Special thanks are due to Lufthansa Technik AG that donated the nose wheel of an A320.

### Notes and References

Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Technische Thermodynamik, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

Corresponding author for ATRA and Antares aircrafts: josef.kallo@dlr.de; Tel: 0049 711 6862-672

[1] S. Eelman, D. L. Daggett, M. Zimmermann, G. Seidel, High Temperature Fuel Cells as Substitution of the Conventional APU in Commercial Aircraft, DGLR-JT2003-183, Deutscher Luft- und Raumfahrtkongress 2003.

[2] V. Roussa, P. Lesagea, S. Begot, D. Candusso, W. Charona, F. Harelc, X. Francois, V. Selinger, C. Schilo, S. Yde-Andersen, Int. J. Hydrogen Energy, 2008, 33, 6755.

[3] P. Schumann, C. Graf, K.A. Friedrich, ECS Transactions, 2008, 12 (1), 651

[4] Airbus International Press Release, Emission free power for civil aircraft: Airbus successfully demonstrates fuel cells in flight, 19 February 2008, http://www.airbus.com/en/presscentre/pressreleases/pressreleases_items/

[5] DLR National Press Release: DLR motor glider Antares takes off in Hamburg – powered by a fuel cell, 7 July 2009 http://www.dlr.de/en/desktopdefault.aspx/tabid-344/1345_read-18278/

[6] DLR National Press Release, Antares DLR-H2 stellt Höhenrekord auf, 21 November 2009 http://www.dlr.de/desktopdefault.aspx/tabid-344/1345_read-21170/

# New Developments for Maritime Fuel Cell Systems

**Finn Vogler, Gerd Würsig,** Germanischer Lloyd AG, Germany

## 1 Introduction

As a result of environmental concerns in shipping the international legislation set by the IMO (International Maritime Organisation) requires the reduction of SOx and NOx emissions from shipping (MARPOL Annex VI). To reduce the SOx emissions in environmental sensitive areas so called SECAs (Sulphur Emission Control Areas) are established for example in the Baltic and North Sea. In these areas a maximum sulphur content of 1.5 % in fuel oil is permitted. This value will be decreased in 2010 to 1.0 %. In 2015 this limit shall be again reduced to 0.1 %. For the NOx emissions a reduction in three steps from 2000 to 2016 is planed. For all three types of diesel engines (low, medium and high speed engines) specific limits per g/kWh are defined. Beneath the inner motor measures also emission scrubbers are permitted [1]. According to the high political pressure a $CO_2$ trade for shipping is currently under discussion at the IMO [2].

The European Union introduces additional laws to reduce ship emissions in European waters. The EU limits the sulphur content in fuel oil to 1.5 % since 2006 for all passenger ships sailing between EU ports. According EU-Directive 2005/33/EG it is planned to reduce the sulphur content in the fuel down to 0.1 % for all ships in European ports, alternatively the use of land based power is permitted [1].

Mainly causes by the strong emission regulations in shipping, the demand of more environmental friendly energy converters, better energy efficiency and emission reduction methods is rising continuously. Several methods like exhaust gas treatment, use of gas as ship fuel either as dual fuel engine or gas motor, electrical onshore connections in the ports, energy efficient energy management and improvements of the whole system (e.g. hull design with low resistance) are currently under discussion. Additionally the fuel cell gets more and more in the focus of the maritime industry to be also a good possibility according to the benefits of high efficiency and low emissions.

## 2 Regulatory Background in Shipping

In shipping the legal requirements are based on the conventions and codes of the International Maritime Organisation (IMO) which are mandatory for all ships in the international trade. The most important conventions are the SOLAS (Safety of Life at Sea) and the MARPOL (Maritime Pollution) conventions. In addition to the IMO legislation the unified requirements of the International Association of Classification Societies (IACS) give guidance on interpretation of special topics with the purpose to harmonize the practice of classification societies. In practice the class societies rules classification and construction incorporate the IMO codes and conventions and the unified requirements. Below these rules the technical standards are applied (Fig. 1).


**Figure 1: Rule Framework in Shipping.**

According to the SOLAS convention it is not allowed to use fuel oils with a flashpoint below 60 °C. The only exceptions are Liquid Natural Gas Tankers under the legislation of the International Gas Carrier Code (IGC-Code). All flag states have to follow this requirement. Therefore in practice, any gas applications are principally forbidden on board. Today all ships which are operated with gas as fuel with a flashpoint below 60 °C are operated by special permission of the local authority, but only for national use. According to the good experiences of the Norwegian government and the rethinking in the use of more clean energy, the IMO started on the request of Norway to develop a guideline for the use of natural gas as ship fuel. These so called provisions for gas as ship fuel will come into force on 1$^{st}$ June 2010 [3], but only for natural gas as fuel for internal combustion engines. It is intended to develop a code for gas as ship fuel in parallel, which includes all kind of gases and may be fuels with a flashpoint below 60 °C for all kinds of energy converters, including the fuel cell. This Code may come into force in 2014 with the regularly update of the SOLAS convention.

Germanischer Lloyd was the first classification society worldwide which published already in 2003 a “Guideline for the use of Fuel Cell Systems on Board of Ships and Boats” [4]. These guidelines have been used successfully for a number of applications. In 2008 and 2009 other classification society published rules for fuel cell systems. Further rules from other classification societies are under development to follow the ongoing development in this field.

## 3 Fuel Cell Systems in Shipping

Fuel cell systems are known for their advantages low noise, no or nearly no NOx emissions and a high efficiency already in the low power range. Furthermore they are of modular design, which leads to benefits for their integration. The big disadvantages of fuel cells are their high costs regardless the fuel cell type and the low specific power which feature more or less strongly to all fuel cell types. The lifetime of a fuel cell stack is today also a big issue for most types of fuel cells. In addition the fuel logistic and the fuel price are obstacles to introduce the technology. Pure hydrogen which is the preferred fuel from a technical point of view is not widespread. Only a few filling stations exist, even less for maritime applications. Nevertheless in regional applications with relatively low power demand, like ferry boats or pleasure boats, it may be possible to establish a sufficient fuel supply with one filling station.

In all other cases, especially in applications with a high power demand another logistic fuel than hydrogen is necessary, according to the fact of the low volumetric energy content of hydrogen (Fig. 2). The required volume for the fuel becomes the most limiting factors for gases as alternative fuels in shipping application.

Fuels other than hydrogen require reformer systems to be applied with fuel cells. Several types of reformer systems are present, but most challenging for them is to get rid of the sulphur, especially in typical maritime fuels. Nevertheless ongoing changes in international regulation which will allow the use of natural gas from mid 2010 and the environmental requirements regarding lower sulphur content in bunker fuel will support the use of reformer systems in the future.

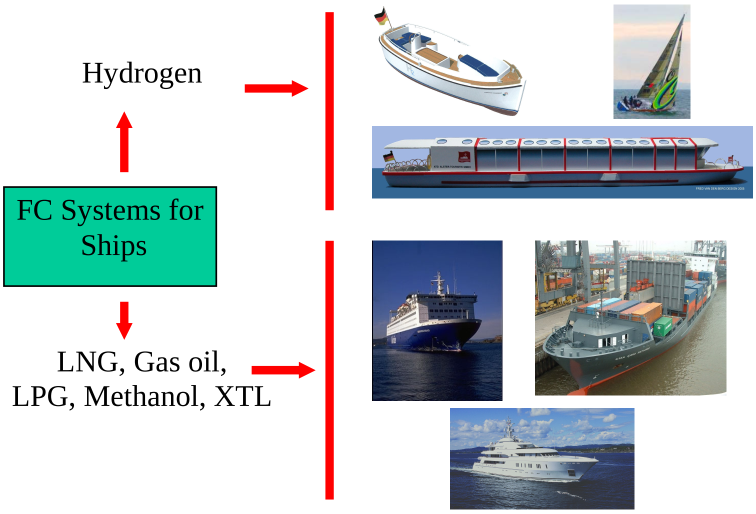



**Figure 2: Which fuel for which application?**

IMO has initiated the development of an international code which will allow the use of different fuel gases and may be also liquid fuels with a flashpoint below 60°C. These developments will also support the use of fuel cell systems in the international shipping.

### 3.1 Suitable FC systems

For the use in shipping low as well as high temperature fuel cells are suitable. In case of use of low temperature fuel cells, the PEMFC (Proton Exchange Membrane Fuel Cell) seems to be the best candidate for the use in naval applications when operated with hydrogen. If the PEMFC is operated with a reformer system it can not compete with conventional internal combustion engines with regard to the efficiency. For the high temperature fuel cells the PAFC (Phosphoric Acid Fuel Cell), MCFC (Molten Carbonate Fuel Cell) and SOFC (Solid Oxide Fuel Cell) is suitable. All three systems normally operate with an upstream reformer system to create a hydrogen rich gas mixture out of hydrocarbons. The PAFC is the mostly deployed fuel cell on commercial bases. Therefore, the PAFC is today an alternative for the use on board of ships. But according to the low efficiency compared to traditional energy converter on board ships, the PAFC is no real opportunity. The MCFC and the SOFC are the most promising fuel cell systems for the use in shipping. The high efficiency and the use of combined heat and power make them suitable for the use in shipping. Today only a few developments of SOFC systems in a reasonable high power range exist. With regard to the status of development the MCFC seem to be the most promising fuel cell system for maritime applications today [5,6,7,8,9].

### 3.2 First applications

In principle fuel cell systems can be used for any maritime application. This starts from pleasure boats, yachts over fishing boats, inland navigational, harbour and supply vessel up to cargo ships and passenger vessel. Even on board of military ships and submarines fuel cells can be used. According to the high power demand of ships (up to 100 MW for main propulsion and 12 MW for auxiliary power for a big container vessel), it has to be mentioned that fuel cell systems at their current status of development are only suitable in niche applications. The main problems are related to the fuel logistics and the fact that fuel cells today can only provide a low power range up to 350 kW. According to the EU funded feasibility study FCShip fuel cell systems with a standardised module size from 500 kW to 1000 kW are needed for shipping applications [10].

In the power range up to 500 kW the fuel cell systems can be used for main propulsion and auxiliary energy. This relates to inland navigational vessel, pleasure boats and yachts, etc. According to the high power demand for propulsion of seagoing ships, the today existing fuel cell system can only be used for auxiliary power. In this area passenger vessel, mega yachts and research vessel will be the first application for fuel cell systems on board. By using 3 to 4 fuel cell systems with a power range up to 500 kW, it is possible to provide the basic load of auxiliary energy for larger seagoing vessel for up to 90 % of the auxiliary energy demand [9].

Fuel cell systems are and will only be used in the areas, where the benefits dominate the costs. The most common example in this respect are the submarines of the German manufacturer HDW used e.g. by the German and Italian navy. Other application areas will be the use of FC-Systems in areas, where the use of internal combustion engines is not permitted (environmental restrictions) and therefore alternative propulsion systems are required.

## 4 Possible Market Potential for Fuel Cell System in Shipping

Germanischer Lloyd has worked on a market analysis for fuel cell systems on seagoing vessels, which was published in the beginning of 2010 [9]. The aim of the study was to identify the possible market and market fields for fuel cell systems on sea going vessels. The study includes beneath the market reflection also the supply logistic and the environmental and economical effects by the use of fuel cell systems in shipping especially for the city of Hamburg.

For the market analysis the world fleet of large commercial vessels (approx. 50.000 vessels) was analysed regarding different reference vessel which represent the most typical ship types. In addition the market for large yachts was included in the evaluation. The analysis based on the use of standardised 500 kW fuel cell modules. For the analysis a partial replacement of auxiliary power on the bases of the standardised modules was assumed. The analysis gives an outlook till 2030.

It can be expected that Mega Yachts, RoRo-Vessel and Cruise Ferries are the first applications for fuel cell systems. These ship types have been analysed more in detail. A market share of fuel cell systems for auxiliary power of 5 % was assumed. The analysis shows that these ship types have a yearly demand for such a technology of about 22 units. This seemed to be a small number, but means a quadrublication of the production capacity of a major MCFC manufacturer in 2008. Additionally it has to be considered that these ship types have only a market share of about 3.5 % of the world fleet!

The outlook over approximately half of the world fleet shows that till 2030 a market volume up to 4250 fuel cell units of 500 kW is possible. The demand for FC systems with a power below 500 kW was not considered in detail but it is obvious that this market is bigger with regard to the number of units. E.g. for small container vessel up to 850 TEU and general cargo vessel there will be an additional market volume for 250 kW fuel cell units up to 600 units till 2030.

These few figures show, that the shipping industry has a very high market potential for fuel cell systems in the future, if the specific maritime requirements can be fulfilled.

Today fuel cell applications in shipping are small scale applications in most cases. Some examples are given below.

## 5 Examples for Successful Fuel Cell Integrations in Shipping

### 5.1 SMART-H2 – Whale watching boat ELDING I

Within the SMART-H2 project (Sustainable Marine & Road Transport on Hydrogen in Iceland) also the marine application of hydrogen will be demonstrated. The main goal of SMART-H2 (2007-2010) will be a demonstration fleet of 20-40 hydrogen vehicles, of different types and using different propulsion technologies and to demonstrate the hydrogen technology onboard a publicly accessible boat. Therefore a 125 ton whale watching boat for 150 passengers was chosen (Fig. 3). The ship's Auxiliary Power Unit (APU) consists of a 10 kW fuel cell operated by compressed hydrogen providing electricity for the ship operation. This enables the boat to switch of the internal combustion engines during whale watching. The ship started its operation in April 2008.


**Figure 3: SMART-H2 – ELDING**

## 5.2 ZEMSHIPS project – FCS ALSTERWASSER

The ZEMSHIPS project (2007-2010), founded by the EU-Life program, has the aim to test practically an emission-free ship operation within an environmental sensitive area and to promote this technology for maritime applications. ZEMSHIPS is the first project in the world to integrate a hydrogen fuelled fuel cells system of this size on a commercial passenger vessel. It combines two fuel cell systems with a peak output of 48 kW each with a 560-V lead gel battery pack (Fig. 4). The prototype FCS ALSTERWASSER has a length of approx. 25.50 metres, a breadth of 5.25 metres and can transport up to 100 passengers. Project partners are ATG Alster Touristik, Germanischer Lloyd, Hamburg University of Applied Science, Hochbahn, hySOLUTIONS, Linde Group, Proton Motor, UJV Nuclear Research Institute. The ship started its operation in 2008-08 [11].

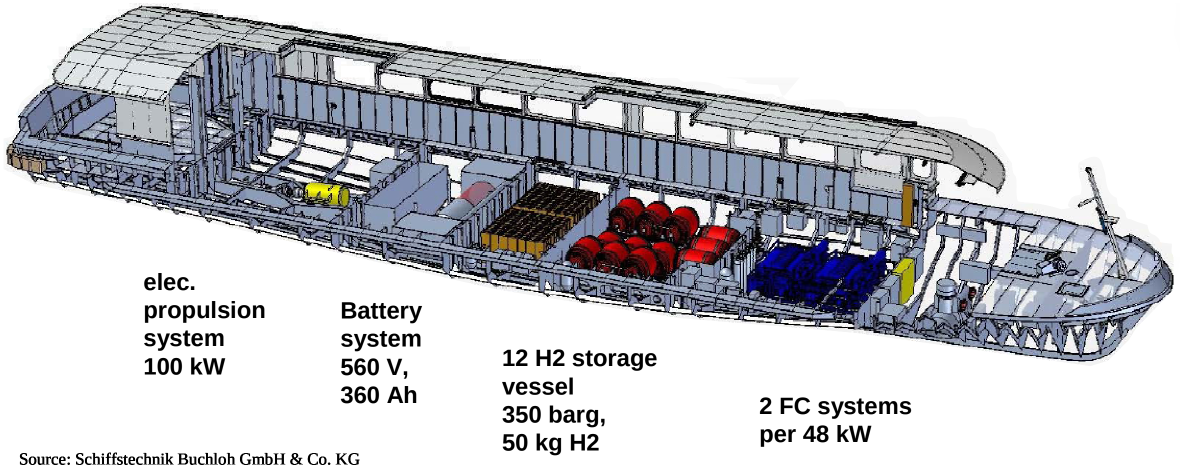



**Figure 4: ZEMSHIPS project – FCS ALSTERWASSER.**

## 5.3 Fuel Cell Boat Amsterdam

The aim of Fuel Cell Boat BV is to realise an inland passenger vessel with a fuel cell system fuelled with hydrogen, including the infrastructure for the refuelling of the vessel. The ship has a length of 22 metres, a breath of 4.25 metres and will be equipped with a fuel cell system of 60-70 kW. The capacity is about 100 passengers. The ship is planned to come in operation summer 2009 [12]. The certification is done by Germanischer Lloyd.

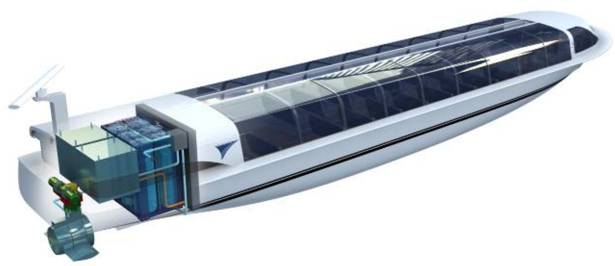


**Figure 5: Fuel Cell Boat Amsterdam.**

## 5.4 Further RUNNING projects

In the following a short overview of some ongoing fuel cell projects is given.

### 5.4.1 MethAPU

The EU founded MethAPU project (Validation of a Renewable Methanol Based Auxiliary Power System for Commercial Vessels) is running from 2006-2009. The objective of this project is to develop and validate marine SOFC of 250 kW running on methanol. The validation will be carried out with a 20 kW SOFC test unit, which will be operated for one year onboard a car carrier. Partners are Wärtsilä, Lloyd’s Register, Wallenius Marine, The university of Genua and Det Norske Veritas. The costs of the program are some € 1.9 million [13].

### 5.4.2 FellowSHIP

FellowSHIP (Fuel Cells For Low Emission Ships) is a three phase project. The overall aim of the project is the development, demonstration and qualification of fuel cell hybrid power pack for ships. The first phase (2003-2005) includes a feasibility study and the basic design development. The second step (2005-2009) comprises the building, testing and demonstration of a 320 kWe fuel cell system on an offshore supply vessel, fuelled with LNG. In the third step (2010-…) the testing, qualification and demonstration of power packs from 1 to 4 MWe is planned. Partners of the project are Wärtsilä Ship Power Automation, MTU Onsite Energy, Vik-Sandvik, Eidesvik, Det Norske Veritas. The Budget is about € 18.75 million [14].

# 6 Outlook on Ongoing Projects

## 6.1 e4ships – Lighthouse project for FC systems in shipping

e4ships is a Lighthouse project founded by the National Innovation Programme – NIP of the German government. The purpose of the project, is to demonstrate that fuel cells can function in ship’s power supply systems under everyday conditions. The project starts in 2009 and will end in 2016. The project is divided in a superior project which includes the steering committee and general topics and three demonstration projects for the realisation of suitable fuel cell systems for ships (Fig.6).

The first project SchIBZ includes the development of a 500 kW MCFC system operated on XTL as fuel. The system shall be tested on a commercial paper carrier in northern Europe.

Pa-X-ell, the second demonstration project, is working on the integration of MCFC systems on board of ships, fuelled by LNG. The first system shall be integrated on a cruise ship. The long term aim is to substitute the auxiliary power systems of RoPax Ferries and Cruise ships. The auxiliary power required for these vessels is in the range of 3000 to 10000 kW per vessel.

The project Hy-Ferry works on the integration of a hybrid system with a 240 kW PEMFC operated by hydrogen in inland waterway and costal vessels.

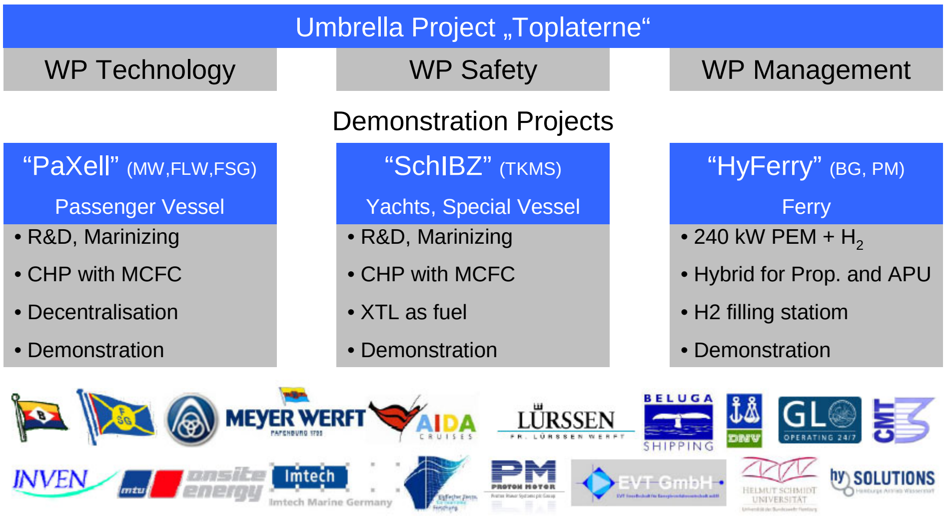



**Figure 6: Structure of e4ships Project.**

## 7 Conclusion

Driven by environmental concerns and the need for sustainable and clean energy in shipping the fuel cell gets in the focus of the maritime industry as a possibility for clean energy conversion on board. Till now fuel cell systems on board of ships are still in the demonstration phase. The only exception is the PEMFC in the submarines from German yard HDW. The PEMFC now starts to come into the market. The high temperature fuel cell, especially the MCFC will probably come into the market during the next 5 to10 years. According to the high power demand in shipping the fuel cell will not replace the existing multi Megawatt main engines of large ships in the foreseeable future. Nevertheless the potential for auxiliary power generation by FC-Systems is much larger than the markets under discussion for large FC-Systems today. In addition this market is less price sensitive than the current target markets of most FC manufacturers. The adoption of fuel cell technology on board will first take place in the replacement of auxiliary power generators. Nevertheless in special markets and applications the fuel cell already today is a good alternative for traditional engines. Especially for pleasure crafts, inland navigational vessel, ferries and also large passenger vessels the fuel cell can be a good alternative. Where a lower power demand or only a regional fuel supply is necessary hydrogen fuelled systems can be applied.

### References

[1] Isensee, J. (2008), “Neue IMO-Regeln für Schiffstreibstoffe und Schiffsabgase”, HANSA International Maritime Journal, 145. Jahrgang, 2008, No. 5, pp. 57-60.

[2] IMO Report. (2007-12-21), “A global levy on marine bunkers, primarily to be applied for the acquisition of CO2 emission quotas through the purchase of CO2 credits”, MEPC 57/4/4:07.

[3] IMO Resolution MSC.285(86), “Interim Guideline on Safety for Natural Gas-Fuelled Engine Installations in Ships”

[4] GL Guideline VI-3-11 (2003), “Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats”, Germanischer Lloyds AG.

[5] USCG Report. (1999), “Marine Fuel Cell Market Analysis”, USCG Research and Development Center, Report No. CG-D01-00.

[6] Bolind A. M. (2000), “An Evaluation of Fuel Cells for Commercial Ship Applications”, The Society of Naval Architects and Marine Engineers, Technical & Research Report R-55.

[7] Bourne, C., Nietsch, T., Griffiths, D. and Morley, J. (2001), “Application of Fuel Cells in Surface Ships”, Rolls-Royse Strategic System Engineering, ETSU F/03/00207/REP.

[8] Kickulies, M. (2005), “Fuel Cell Power for Marine Applications”, Fuel Cell Bull 2005;9:12-5

[9] GL Report (2010-03), “Endbericht zur Marktstudie Brennstoffzellensysteme in der Seefahrt”

[10] Bøhlerengen, B., Würsig, G., Viviani, Weinberger, Skjølsvik and Zhou (2004), “Synthesis of open problems and Roadmaps for future RTD, EU project FC Ship – Fuel Cell Technology in Ships, DTR-5.2-06.2004

[11] Project internet page, http://www.zemships.eu/, 2009-03-25

[12] Project internet page, http://www.fuelcellboat.nl/, 2009-03-25

[13] Project internet page, http://www.methapu.eu/, 2009-03-25

[14] Project internet page, http://www.fuelcellship.com/, 2009-03-25

# Bio-methanol Fuel Cell Systems for Ships

**Paul van den Oosterkamp**, **Anne-Marie Tjeerdsma**, Energy research Centre of the Netherlands, The Netherlands
**Mark Couwenberg**, Damen Shipyards, The Netherlands

## 1 Introduction

On board of ships electricity is usually generated by diesel generator sets. Ship operators are however more and more confronted with emission regulations. Emission of NOx, SOx, particulate matter (PM) and volatile organic compounds (VOC) are becoming increasingly restricted, especially in ports. Besides that, the idea that a very expensive climate crisis is coming towards us is becoming more and more accepted. This results in an increasing focus on reduction of greenhouse gasses, especially $CO_2$. For the near future (less than 5 years) it may be relatively easy for ships to fulfil the emission regulations. However, this is much less certain for the midterm future. A possible solution to produce electricity on board ships without any harmful gaseous emission is to use fuel cells fuelled by a renewable fuel [1]. A very promising fuel would be bio-methanol which is produced (e.g.) from glycerine, a waste product from biological origin. Fuel cells might provide a very efficient means of converting this bio-fuel into electricity.

## 2 Fuel Cells on Board of Ships

Fuel cells are being developed for decades. The focus has mostly been on automobile applications and stationary electricity and heat generation. As an example, figure 1 shows a Mercedes Benz A-class car equipped with a methanol-fuelled fuel cell system at the finish of a 12 days, 3000 miles+ test drive across the United States.


**Figure 1: Mercedes Benz A class with methanol fuelled fuel cell system [2].**

The use of methanol as fuel for fuel cell cars was a topic of significant R&D in the 90's of the previous century. Methanol as fuel was abandoned in those days for reasons of safety and health, in particular related to possible contamination of water. This is an issue related to the consumer use of methanol fuel. For application of methanol as fuel for ships this is not a serious issue as it is a much more industrial application, not a consumer related issue. A number of studies have already been conducted for the use of fuel cells ships on ships and currently fuel cells are applied in a number of pilot and commercial projects. We believe that with our proposed system configuration a large number of different marine applications will become within reach. This case study provides answers to the following questions:

- What requirements does a fuel cell system have to fulfil for a given ship type and application?
- What would be the preferred system configuration? Which lifetime is required?
- What will the efficiency of the preferred system be and besides fuel, what other utilities are needed?
- What dimensions and weight will a possible system have?
- What constraints with respect to safety, regulations, fuel logistics etc there will be?
- What further steps are needed to develop such a system?

## 3 Project Organization and Tasks

The project was executed with a number of key partners, covering the shipbuilding industry, the ship operating industry, the fuel cell R&D and the safety and certification issues. *Damen Shipyards Gorinchem* (Netherlands), builds a large variety of ship types worldwide. The main task of Damen was to set up a program of requirements. *Wagenborg Shipping Delfzijl* is a ship operator and owns a large number of cargo ships. Wagenborg selected a representative ship type as a base case to integrate a methanol based fuel cell system and also advised on the basic requirements. *Energy research Centre Netherlands* (ECN) is a major European research centre focusing on energy research development and consultancy and has experience with methanol in relation to fuel cells. ECN's task was to assess the basic system configuration and determine the main parameters of such a system, being efficiency, dimensions and weight. *Ecofy*s is a consultancy company based in Utrecht in the field of energy savings and sustainable energy solutions. Ecofys summarized the main issues with respect to safety, regulations and fuel logistics.

## 4 Requirements and Starting Points

As benchmark for the fuel cell system a representative ship type from the Wagenborg fleet has been chosen. The vessel type is a multipurpose dry cargo carrier with a total loading capacity of approximately 7300 ton. A picture of such vessel is shown in figure 2, the MS Loireborg, built by Royal Niestern Sander, delivered in 2008.


**Figure 2: The dry cargo carrier (7300 ton).**

Although there is a large variation in dimensions of similar ship types, the electrical power system is thought to be representative for a lot of vessels. The electrical installation is shown in a one-line diagram in figure 3.

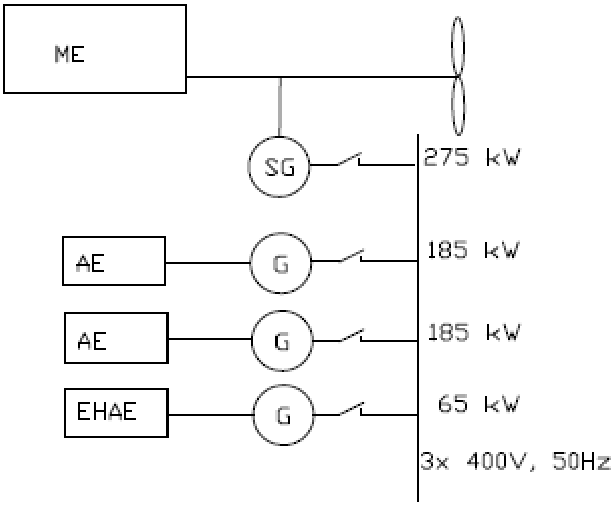



**Figure 3: Electrical system lay out (NE=Main Engine, AE =Auxiliary Engine, EHAE=Emergency/Harbour auxiliary engine, SG= shaft generator).**

The proposed fuel cell system will replace one auxiliary engine. When the vessel is at sea, usually the shaft generator is taking care for the total electricity supply on board. When the vessel is approaching a port, the auxiliary engines are switched on.

The *required lifetime of the fuel cell* was defined as 16,000 hr or about two years. As most ships have a maintenance interval of 2.5 years, this will also count for the fuel cell system. Within these 2.5 years the fuel cell system is expected to run more or less permanently. The *electric load balance* has been studied and yields a *nominal power* of 125 electrical kW and a *peak power* 185 electrical kW, this peak power shall be produced for a minimum of 5 minutes time. With these specifications a fuel cell system would be able to generate power for the majority of operations while in port. At the same time the total amount of installed power is enough in all situations. The fuel cell system should be arranged as the ‘first’ source of auxiliary power. In case the fuel cell system considers or expects the electrical load to be too high, the auxiliary diesel engine should be started up automatically. During switchover to sea-mode, the shaft generator should be able to take over from the fuel cell system. The exact utilization of the fuel cell system and shaft generator will depend on economic parameters. Concerning *power dynamics*, the maximum allowable variations in the power supply are defined as a variation in voltage between +6 and -10% of nominal voltage and a variation in frequency of: +/- 5%. The volume and weight of the fuel cell system should preferably not be beyond the size and weight of a diesel power generator. Other parameters as vibrations and ship motion (including deceleration in the case of a ship collision) are determined as well. Germanischer Lloyd has done a lot of work in the field of fuel cells and developed a complete set of descriptive rules which can be applied to the fuel cell system proposed in this study. The fuel cell system will need to obey all applicable *rules and regulations*.

## 5 System Evaluation

In the initial project phase, a choice was made regarding the type of fuel cell for this application. In principle, a choice can be made between DMFC, PEMFC, MCFC, SOFC and PAFC. Based on the applicable power range for this application and the availability of stacks, the PEMFC technology and SOFC technology were short listed as design case for this application.

The goal of the fuel cell system is to generate electricity from methanol. However, in order to utilize a PEMFC or a SOFC, the methanol feed needs to be converted (reformed) to a hydrogen rich gas. Reforming can be performed in two ways: by steam reforming or by auto thermal reforming. An advantage of auto thermal reforming is that dynamic operation is possible. However, in our application the system will operate stationary. Another difference between auto thermal and steam reforming is the efficiency. In general, steam reforming can be performed at higher efficiencies. Therefore, steam reforming is chosen as the preferred methanol conversion step. Figure 4 shows the conceptual lay-out of the PEMFC based system. The reformer product gas is sent to the preferential oxidation unit to reduce carbon monoxide to a level below 10 ppm CO in order to minimize degradation of the anode (noble metal) catalyst in the PEMFC.

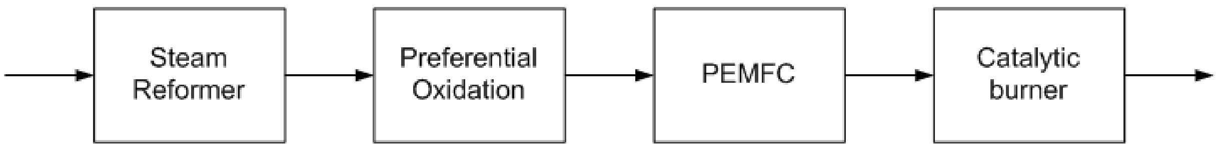



**Figure 4: Conceptual lay-out of the methanol based steam reforming system.**

The goal of the SOFC system is similar to the PEMFC system: To reform methanol to a hydrogen rich stream and utilize this to generate electricity. Here reforming is performed by steam reforming as well (figure 5). In this system there is no need for a gas clean up like preferential oxidation, because the carbon monoxide present in the reformate is not toxic, but rather a fuel for the SOFC. The SOFC system lay-out is therefore simpler. The SOFC is operated at high temperature (700-800 °C). Therefore, it is necessary to preheat the reformate before it enters the SOFC. The off gasses from the fuel cell are supplied to a burner. The heat generated in the burner is utilized for steam reforming as well as for heating up the reformate.

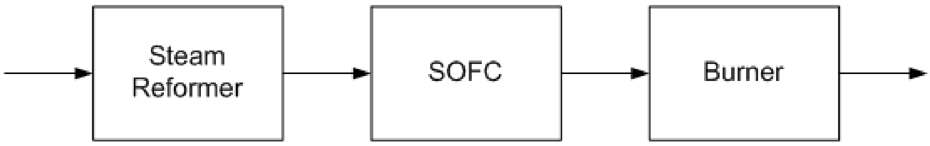



**Figure 5: Conceptual lay-out of the methanol based steam reforming system.**

In the PEMFC system and the SOFC system, batteries are included to secure the electricity supply upon significant demand increase (up to 54 kW). Both systems should be able to respond to such demand changes within ten minutes. Therefore, the required batteries should be similar for both systems.

## 6 Results and Discussion

The PEMFC system is presented schematically in figure 6, indicating that methanol and water are pumped into the system, heated, evaporated and supplied to the steam reformer (operating at 250 °C). In the steam reformer the following reactions take place [3–5]:

$$CH_3OH + H_2O \leftrightarrow CO_2 + 3H_2 \qquad \Delta H = +48.8\ kJ/mol$$

$$CH_3OH \leftrightarrow CO + 2H_2 \qquad \Delta H = +89.2\ kJ/mol$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41.0\, kJ/mol$$

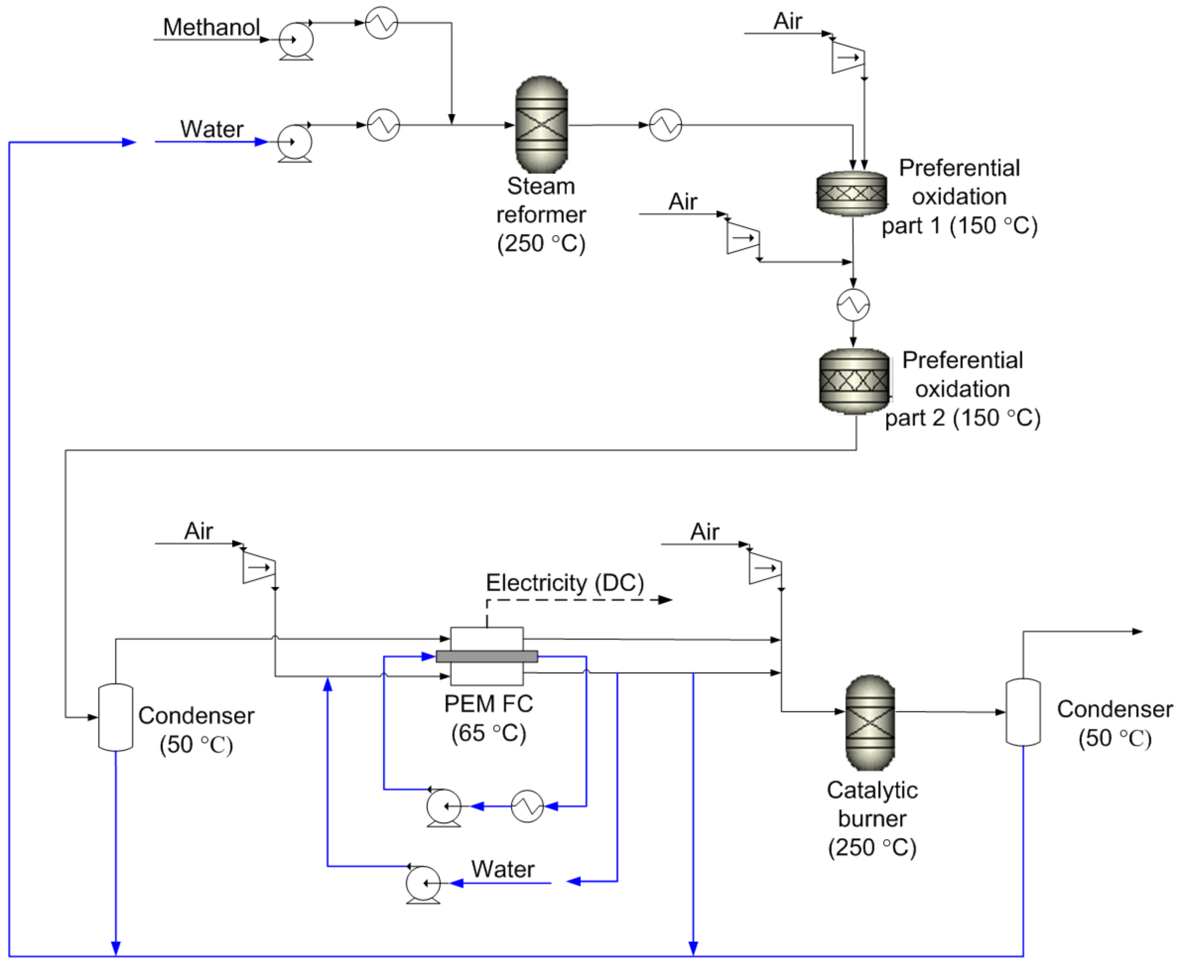



**Figure 6: Conceptual flow scheme of the PEMFC system.**

Reaction (1) is the steam reforming reaction, reaction (2) is the methanol decomposition reaction, and reaction (3) is the water-gas shift reaction. The first two reactions are endothermic, while the third reaction is slightly exothermic. The overall reaction in the steam reformer is endothermic, so that external heat has to be provided. The off gas from the catalytic afterburner will be cooled down from 250 $^0$C to 50 $^0$C, providing sensible heat for co-generation. Using the same methodology, also a design case with SOFC stacks technology was analyzed. The conceptual flow scheme is given in figure 7.

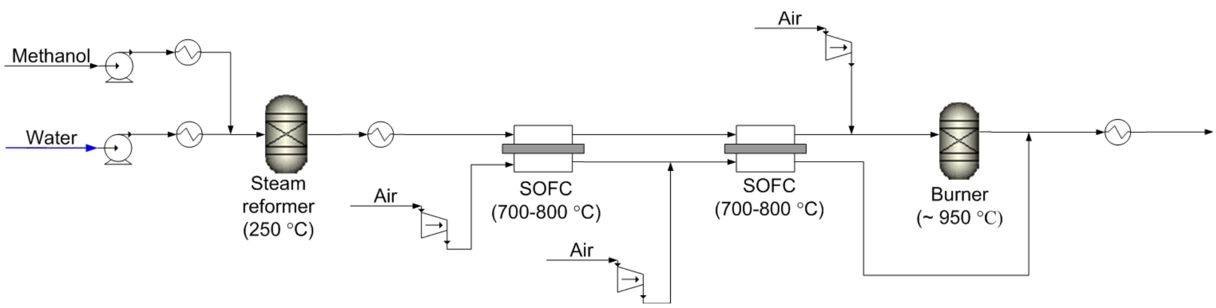



**Figure 7: Conceptual flow scheme of the SOFC system.**

In table 1 the main operating characteristics of the PEMFC and SOFC system are compared.

**Table 1: Overview of simulation results.**

| | PEMFC system | SOFC system |
|---|---|---|
| Net electrical efficiency (%) | 41.6 | 42.8 |
| Total net efficiency (electrical and heat) (%) | 41.6 | 69 |
| Additional cold utility requirement (kW) | 152 | 25 |
| Water recycle possible (if pure methanol is used) | Yes | No |

Table 2 shows the other system characteristics. Based on the availability and the lifetime of the stacks, the PEMFC case was selected as most promising option.

**Table 2: Other system characteristics calculated.**

| | PEMFC system | SOFC system |
|---|---|---|
| Commercially available FC stack (kW) | ≤ 100 kW | ≤ 1 kW |
| Lifetime stack according to supplier (h) | 20 000[1] | 1 000[2] |
| Complete system size ($m^3$) | 9.3 | 9.0 |
| Fuel storage (pure methanol) ($m^3$) | 51 | 50 |
| Fuel storage (mixture) ($m^3$) | 81 | 78 |

## 7 Conclusions and Outlook

The electrical efficiency of the SOFC system performs marginally better than the PEMFC (42.8 % versus 41.6 %, respectively). In terms of total system efficiency the SOFC system scores significantly better, as generated heat can be utilized to heat thermal oil on the ship for co-generation of heat. (69 % for SOFC in comparison to 41.6 % for the PEMFC). Beside the high system efficiency, there are also downsides to the SOFC system. Water supply will always be necessary for the SOFC system, as not all water can be recycled in the system. The PEMFC system can work without a water supply, if pure methanol is utilized as a fuel. Another downside of the SOFC system is that SOFC stacks are currently available to a maximum of 1-2 kW. This would mean that more than a hundred stacks would be necessary in the system. This is not practical. Furthermore, the lifetime of the SOFC stacks (1,000 h) is distinctly below the desired lifetime of 16,000 hours.

The size calculations indicate that the methanol storage is the most important factor in terms of overall system size. If a water-methanol mixture is utilized (instead of pure methanol) the size of the feed storage increases with about 60 % (from ~50 $m^3$ to ~ 80 $m^3$). The calculations also show that in terms of size, there is little difference between the PEMFC and SOFC systems.

---

[1] According to NedStack product information

[2] According to Staxera product information

As an overall conclusion, we conclude that a PEMFC based fuel cell system as the most promising, with the generation of 125 kW at efficiency of 41.6% in a 9 $m^3$ system. Safety regulations and fuel logistics are important exogenic parameters that have to be taken into account. Furthermore, the proposed fuel provides a $CO_2$ neutral chain with no or hardly any harmful emissions, while the price of the methanol fuel is comparable to that of diesel oil.

A follow-up of the study presented here is the preparation of a complete design for a 185 kW methanol fuel cell system on board of ships, taking into consideration all required regulations that are inherent to a ship operation and to the safety of a hydrogen production unit in combination with a fuel cell. This follow-up is currently being investigated.

**References**

[1] De Bruijn, F.A., Rietveld, G., van den Brink, R.W., “Hydrogen Production and Fuel Cells as bridging technologies towards a sustainable energy system”, In: Catalysis for Renewables: From feedstock to Energy Production, Eds. G. Centi and R.A. van Santen, Wiley-VCH Verlag, Weinheim, 2007, pp.299-336.

[2] http://www.hycar.de, accessed May 2009

[3] Delsman, E.R., Microstructured Reactors for a Portable Hydrogen Production Unit, PhD thesis (2005).

[4] Van den Oosterkamp, P.F., “Synthesis gas general: Industrial Processes and Relevant Engineering Issues”, Encyclopaedia of Catalysis, (Wiley), (2002)

[5] Bartholomew, C.H, Farrauto, R.J., Fundamentals of industrial catalytic processes, second edition, Chapter 6 Hydrogen Production and Synthesis Gas Reactions, pp 339-486, John Wiley & Sons, Hoboken, New Jersey, US, 2006

# Development of an Ultra Compact CPOX Reactor for Diesel Fuel

**Go Motohashi**, **Hitoshi Mikami**, **Jun Iwamoto**, Honda R&D Co., Ltd., Japan
**Subir Roychoudhury**, Precision Combustion, Inc., USA

## 1 Background

Environmental conservation awareness is increasing all over the world. As a result, intensification of emission regulation in automotives has become more stringent, and it has been extended not only to HC, CO, NOx, and particulates, but also to $CO_2$. Therefore, further improvement of automotive exhaust gas emission and fuel consumption are required for internal combustion (IC) engines. This includes Diesel Engines, which have a high market share in EU because of its high torque and low fuel consumption. Even diesel engines will be required to achieve lower exhaust emissions and improved fuel economy. However, it is difficult to further reduce diesel engine emissions with existing technology. Hence, novel technical solutions are required.

One way to address these issues is by improving combustion and after-treatment efficiency by dosing hydrogen and/or other reducing-gas into the engine intake and/or upstream of the exhaust catalyst [1,2]. To do this an on-board reforming reactor, which can synthesis hydrogen and/or other reductant gas using diesel fuel, is needed.

New powertrains, such as Partial Hybrid Electric Vehicles (PHEV), are an alternative approach towards meeting these stringent emission regulations. Especially, Series HEVs, in which the engine is used only for power generation i.e. as an Auxiliary Power Unit (APU), is one of the most effective systems for reduction of $CO_2$ emissions. In addition, recent approaches which replace the IC engine in favour of fuel cells such as Solid Oxide Fuel Cells (SOFC) with onboard reforming further improve power generation efficiency [3] .

Reforming reactors however have been primarily developed for stationary applications. The key requirements for these reforming reactors include high conversion of fuels into hydrogen and durability at constant load for tens of thousands of hours. Generally, steam reforming (SR) and auto thermal reforming (ATR) are chosen for those uses [4,5]. These reaction products contain higher concentrations of hydrogen via endothermic reactions or heat-independent reactions from hydrocarbon fuels, steam, and air, as needed.

In addition to the above features, high adaptability to transients e.g. start up and turndown, low HC in syngas, compactness, reasonable cost, and sufficient durability despite transient operation must also be realized in consideration of aspects required for automobile use. There is also a difference in the fuels of interest and lack of water. For instance, methane or natural gas is the primary fuel used for stationary applications, but for on-board applications, a liquid fuel such as diesel or gasoline has to be used in keeping with the existing fuelling infrastructure.

A diesel-fuelled, experimental reforming reactor, suitable for on-board automobile applications, was developed. The goal was to design a reforming reactor that was distinctly different from conventional reformers for stationary or fuel cell applications.

## 2 Reforming Reactor

In order to satisfy the requirements for such an on-board reformer, a reforming reactor was designed and fabricated. It had two novel features. The first was waterless CPOX of diesel on a radial configuration. The second was a suitable fuelling strategy capable of operating under rapid transients.

### 2.1 Reactor design

The key design emphasis was on compactness and high conversion of fuel to hydrogen. Dry or waterless CPOX, which produces hydrogen using only fuel and air was chosen as the reforming approach. This permits use of a simple reforming reactor by avoiding use of steam, while performing at a relatively high reforming efficiency because of a use of catalyst.

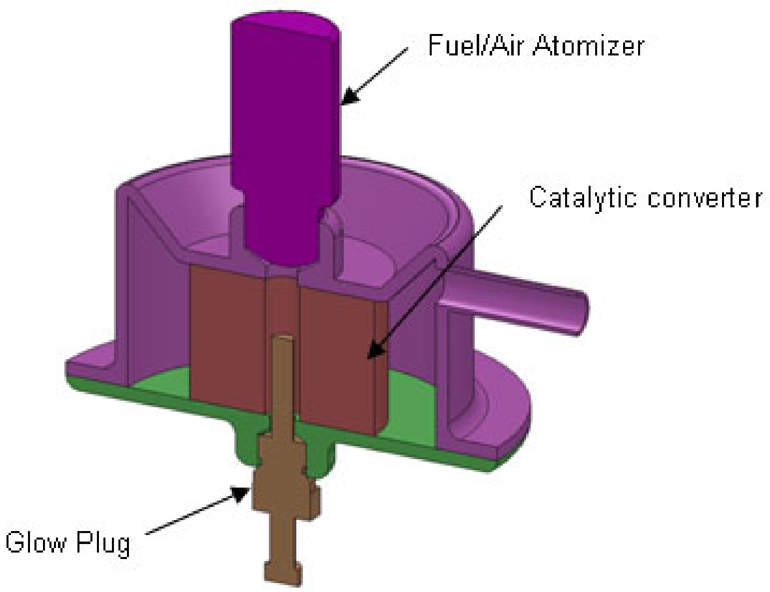


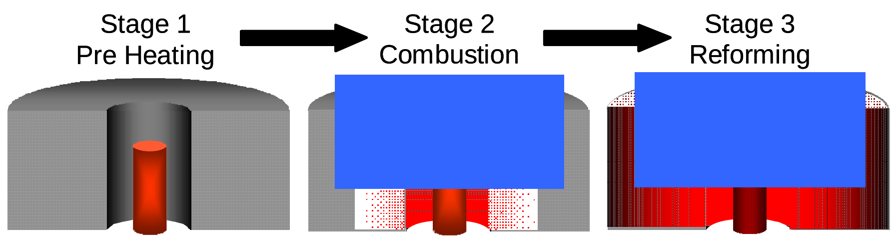

**Figure 1: Schematic diagram of a radial flow dry CPOX reforming reactor.**

Figure 1 shows a schematic diagram of the CPOX reforming reactor. This reactor comprises primarily of a catalytic converter which produces hydrogen using the fuel and air, a glow plug capable of raising the temperature of the catalytic converter to activation temperature quickly, and an atomizer capable of uniformly mixing fuel and air. These components are additionally arranged within close proximity. Consequently, the reactor was extremely compact at a total volume of approximately 150 cc (catalyst size: 20 cc). In order to achieve compactness, a radial flow design was adopted in which the flow of inlet gas to the catalytic converter passes radially through the catalyst. In order to realize a radial flow system, a substrate with a three-dimensional network structure was used [6,7]. There have been various reports on research into dry CPOX using diesel fuel, but those systems generally had a heating section to heat up the air before introducing it to the reactor, or a vaporizing section and mixing section to make a uniform mixture of fuel and air to achieve fast startability and high conversion to hydrogen. The developed reactor, by contrast, is able to achieve these properties required without these sections by using an atomizer to enable a very fine and uniform mixture of fuel and air in a compact space.

## 2.2 Fuelling strategy in transient state

Transient reformer operation, such as start up and syngas flow rate change, requires rapid and stable operation with minimum higher HC breakthrough. We employed a fuelling strategy to enable this. It is represented in Figure 2. The operation consists of three stages and is dependent on the temperature of the catalytic converter.

In Stage 1 (pre heating), the glow plug is switched on and heats the catalytic converter until it reaches the catalyst activation temperature (in the figure, it is posited as 400 °C). At this time, neither fuel nor air has been fed into the reactor. Next, in Stage 2 (combustion), fuel and air are co-fed. Here, the catalyst is further heated by the combustion reaction. In this step, fuel and air flow rate and O/C ratio are adjusted for lean operation for rapid heat up with low HC emission. This permits quick transition to Stage 3 (reforming). Finally, when the temperature of the catalytic converter reaches the optimal temperature (in the figure, it is posited as 800 °C) suitable for dry CPOX reaction, operation shifts to Stage 3 and the fuel and air flow rate is changed to a condition in which the dry CPOX reaction is efficiently sustained by heat-independent operation. The power to the glow plug is also switched off and the system shifts to steady-state. In Stage 3, the dry CPOX reaction proceeds sufficiently and the temperature range is set (this time from 800 °C to 1,100 °C) so as to avoid thermal degradation of the catalyst. Syngas flow rate change is implemented by varying the fuel flow rate while keeping within this temperature range. Despite the aforementioned strategy, the duration of Stage 2 during transient operation was a few seconds. Further reduction in response time was made possible via the use a quick response solenoid valve as the fuel flow controller.




| | | | |
|---|---|---|---|
| Temp. on the upper of the catalyst | RT～400℃ | 400℃～800℃ | 800℃~1100℃ |
| Glow plug | ON | ON | OFF |
| Fuel/air | Not fed | fed | fed |
| O/C | — | Lean than STEP3 | about 1.0 |

**Figure 2: Image of the control logic on a dry CPOX reforming reactor.**

## 3 Performance

### 3.1 Steady state performance

Figure 3 shows the steady state performance result at several fuel and air flow rates and O/C ratios. This result shows that an optimal flow rate of fuel and air exists in order to achieve high hydrogen production efficiency.

Conditions which showed best performance (i.e. high hydrogen concentration and low THC concentration) were at a fuel flow rate=3.81 g/min., air flow rate=17.0 L/min., O/C=1.05 (Figure 3) with hydrogen concentration of 20.9 %. This corresponds to greater than 80 % hydrogen yield and to about 5L/min. of hydrogen production. In addition, THC concentration at this condition was at 0.65 %.

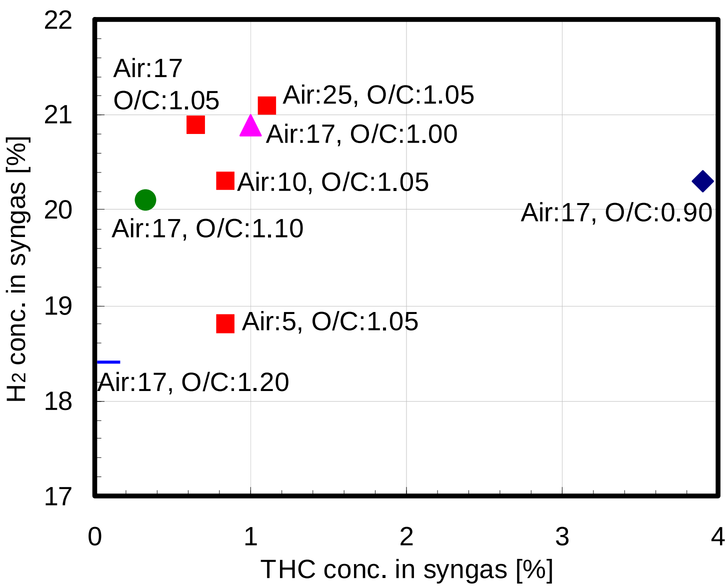



**Figure 3: Steady state performance of dry CPOX at several fuel/air condition.**

### 3.2 Transient performance

With the aforementioned strategy, start up performance was evaluated. Operating condition for each Stage is shown in Table 1. Note that the value of O/C in Stage 2 was higher than in Stage 3.

**Table 1: Operation condition on transient performance evaluation.**

| | Stage 2 | Stage 3 |
|---|---|---|
| **Fuel** | 1.77 g/min | 3.81 g/min |
| **Air** | 15 L/min | 17 L/min |
| **O/C** | 2.00 | 1.05 |
| **Operation range** | 400 ~800 | 800 ~1000 |

### 3.3 Start up performance

During start up, the temperature rises quickly and reaches reforming temperature without overshoot. Hydrogen concentration increase follows the temperature ramp. Start up time was defined as the time taken to reach 90 % of steady state hydrogen concentration. This period was observed to be 30 seconds after cold start at room temperature. Figure 4 shows the behaviour of hydrogen concentration in syngas and temperature on catalytic converter during start-up performance test.

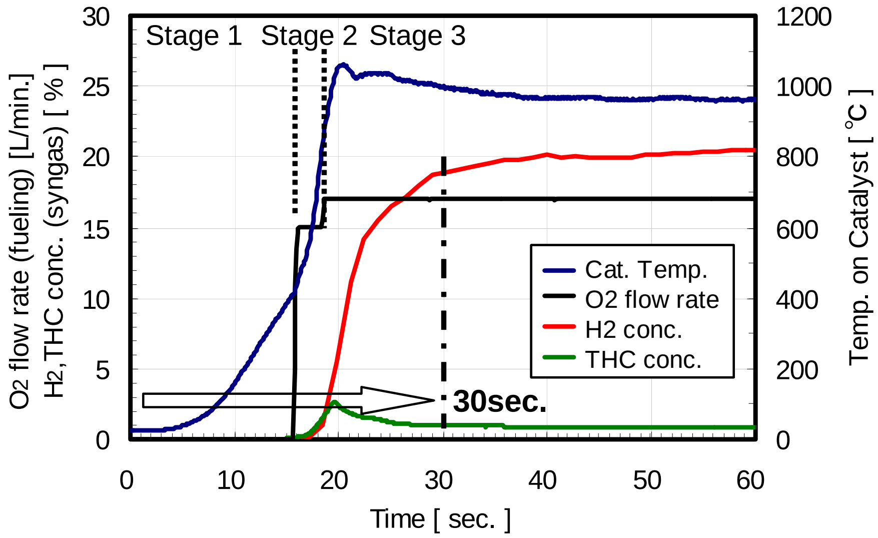



**Figure 4: Start up performance of dry CPOX by our fuelling strategy.**

### 3.4 $H_2$ production change performance

Next, the rate of change of hydrogen production was examined as a function of the fuelling strategy used during Stage 3. The maximum and minimum hydrogen production rates were identified (Table 2).

**Table 2: Operation condition and result on $H_2$ production change performance evaluation.**

| | **Max $H_2$ production** | **Min $H_2$ production** |
|---|---|---|
| **Fuel** | 3.81 g/min | 1.90 g/min |
| **Air** | 17 L/min | 8.5 L/min |
| **O/C** | 1.05 | 1.05 |
| **Cat. Temp.** | 1000 (approx.) | 950 (approx.) |
| **$H_2$ concentration** | 20.9 % | 19.8 % |
| **$H_2$ production** | 1.05 | 1.05 |

Figure 5 shows the transient behaviour of hydrogen and THC concentration in syngas, fuelling air flow rate, and temperature within the catalytic converter. Hydrogen production changed quickly and in a stable manner form 2.3L/min. to 5.2L/min. No transient temperature spikes or other such phenomena were observed. This was not possible with slow response fuel controllers.

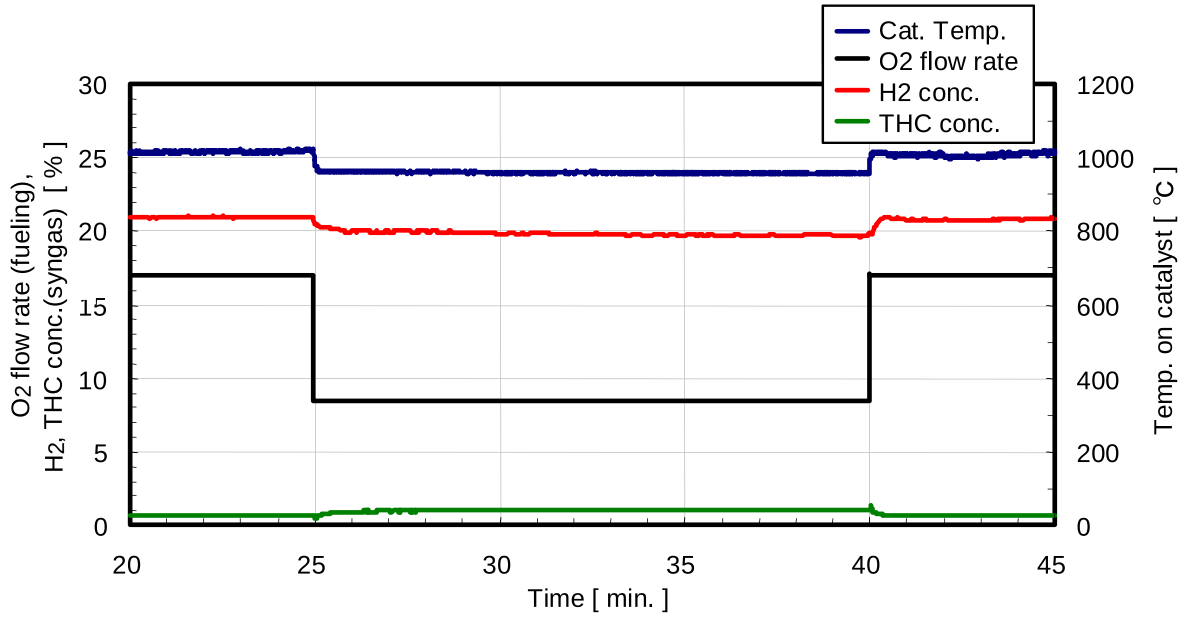



**Figure 5: $H_2$ production change performance behaviour of dry CPOX.**

## 4 Conclusion

Experimental development of an on-board diesel reforming reactor suitable for an automobile was completed. A reforming reactor was demonstrated with high conversion to hydrogen, good transient response, including start up and syngas flow-rate change, and low HC breakthrough within an ultra compact package. This work confirmed the possibility of on board reforming for automobile applications.

### References

[1] L. McWilliam, T. Megaritis, H. Zhao, Experimental Investigation of the Effects of Combined Hydrogen and Diesel Combustion on the Emissions of a HSDI Diesel Engine, SAE Paper 2008-01-1787 (2008)

[2] K. Theinnoi, S. Sitshebo, A. Tsolakis, V. Houel, R. R. Rajaram, Hydrogen Promotion of Low-Temperature Passive Hydrocarbon-Selective Catalytic Reduction (SCR) over a Silver Catalyst, Energy Fuels Vol22 No.6 4109-4114 (2008)

[3] J. J. Botti, M. J. Grieve, J. A. MacBain, Electric Vehicle Range Extension Using an SOFC APU, SAE Paper 2005-01-1172 (2005)

[4] R. Gerd, H. Viktor, Hydrogen for fuel cells from ethanol by steam-reforming, partial-oxidation and combined auto-thermal reforming: A thermodynamic analysis, J. Power Sources Vol.185 No.2 1293-1304 (2008)

[5] J. Pasel, J. Meissner, Z. Pors, R.c. Samsun, A. Tschauder, R. Peters, Autothermal reforming of commercial Jet A-1 on a 5kWe scale, Int. J. Hydrogen Energy Vol. 32 No.18 4847-4858 (2007)

[6] S. Roychoudhury, M. Castaldi, M. Lyubovsky, R. LaPierre, S. Ahmed, Miclrolith catalytic reactor for reforming *iso*-octane-based fuels into hydrogen, J. Power Sources 152 75-86 (2005)

[7] M. Lyubovsky, H. Karim, P. Menacherry, S. Boorse, R. Lapierre, W. C. Pfefferle, S. Roychoudhury, Complete and partial catalytic oxidation of methane over substrates with enhanced transport properties, Catal. Today Vol.83 No.1/4 183-197 (2003)

# Development Progress of Small Fuel Cell Systems for Future Vehicles

**Michael Bauer**, **Georg Götz**, **Wolfgang Strobl**, BMW Group Research and Technology, Germany

## 1 Introduction

One of the biggest challenges for car makers in the future is the introduction of hydrogen as an alternative energy carrier. The BMW Group has been continuously working on hydrogen vehicles for over 30 years.

*BMW Group Research and Technology* is cooperating with *UTC Power* in order to investigate the feasibility of PEM fuel cell systems as an Auxiliary Power Unit (APU) for hydrogen vehicles. In the second decade of cooperation, the major challenges such as lifetime, freeze capability and dynamic response are mostly tackled.

Today's vehicle concepts use an internal combustion engine (ICE) to ensure the driving performance in urban and non-urban areas. Electrical energy, needed for the auxiliaries, will be generated with the alternator to supply these components in the car. This electricity is produced in an uneconomic way with approximately 20 % efficiency due to the serial connection of the IC engine and the generator.

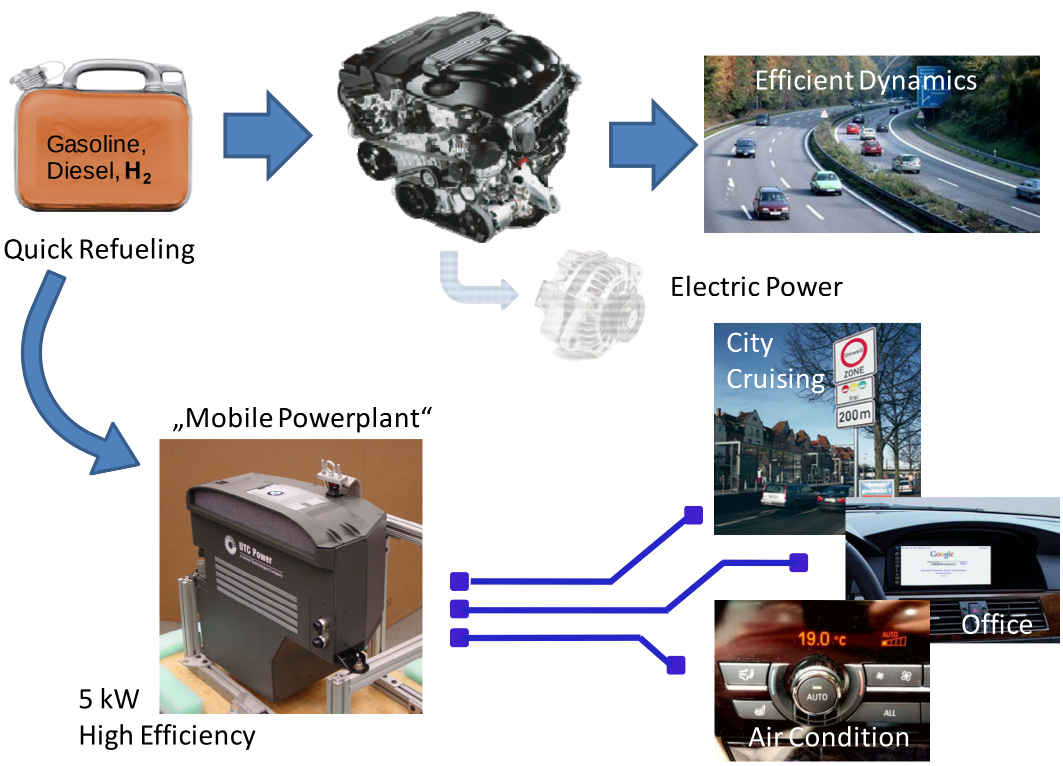



**Figure 1: Energy management and new customer benefits.**

Fuel cells offer with a direct conversion from fuel to electrical energy a highly efficient solution to ensure the demand of energy for electric vehicle components. Due to the implementation of this additional energy converter an independent supply with electricity in the car will be feasible. Figure 1 shows one future vehicle concept with two primary energy converters: internal combustion engine and a small fuel cell. The ICE is mainly used to drive the car in non urban areas, in which high power is needed. In urban areas, a small fuel cell can also cover besides the supply of the board-net, the needed energy for cruising at low speed.

This mobile fuel cell power plant is also capable to offer the customer additional benefits such as mobile office applications and air conditioning, even if the engine is not running. Using hydrogen as fuel, a zero emission vehicle in urban regions is reasonable by keeping the costs for the fuel cell as low as possible. With a power rating from 5 to 10 kW, the fuel cell can be optimized as an auxiliary power unit.

## 2 Technology

Designing an APU for cars, a system with lower volumetric and gravimetric power density compared to fuel cells supplying the drive train can be used. As a result, the main focus of this application is the highest efficiency of the whole system. In 13 years of development, an ultra-low pressure system promises the best solution for the application as a small fuel cell. Because the system operates at low pressure, a low power fan instead of a high power compressor can be used to provide air flow to the stack. The power required for all balance of plant parts is only one to two percent compared to the maximum power output. In Figure 2, the improvement of the system efficiency from GEN II (1999) to GEN IV (2010) is shown. All systems are rated at 5 kW output power.

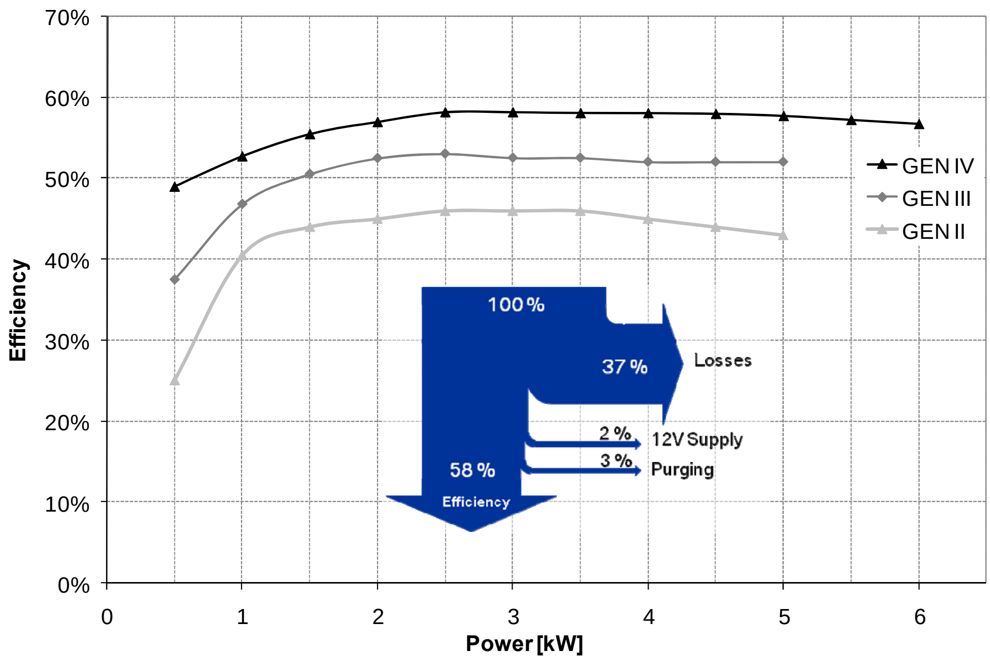



**Figure 2: Efficiency of APU Generations II to IV.**

Graphite porous bipolar plates are used to manage the water produced in the stack. Water diffusion through the bipolar plates enables the direct humidification of the reactants in the flow fields which ensures that the membrane is properly hydrated under all operating conditions. Additionally water removal from the cathode channels is enhanced. These measures result in an extended lifetime of the stack. Figure 3 shows the decrease of the stack voltage against the lifetime. Under test conditions that simulate use in a vehicle, the current GEN IV system reaches a lifetime of 5000 h in which a degradation of 5.5 µV/h per cell occurs. Also one important topic for the APU application is the dynamic response if the load changes rapidly. To replace the vehicle alternator with a battery, the fuel cell voltage must be above a certain limit at all times. Extreme testing with sudden changes from almost zero to full load is shown in figure 3. The response time is in this case is below 5 ms.

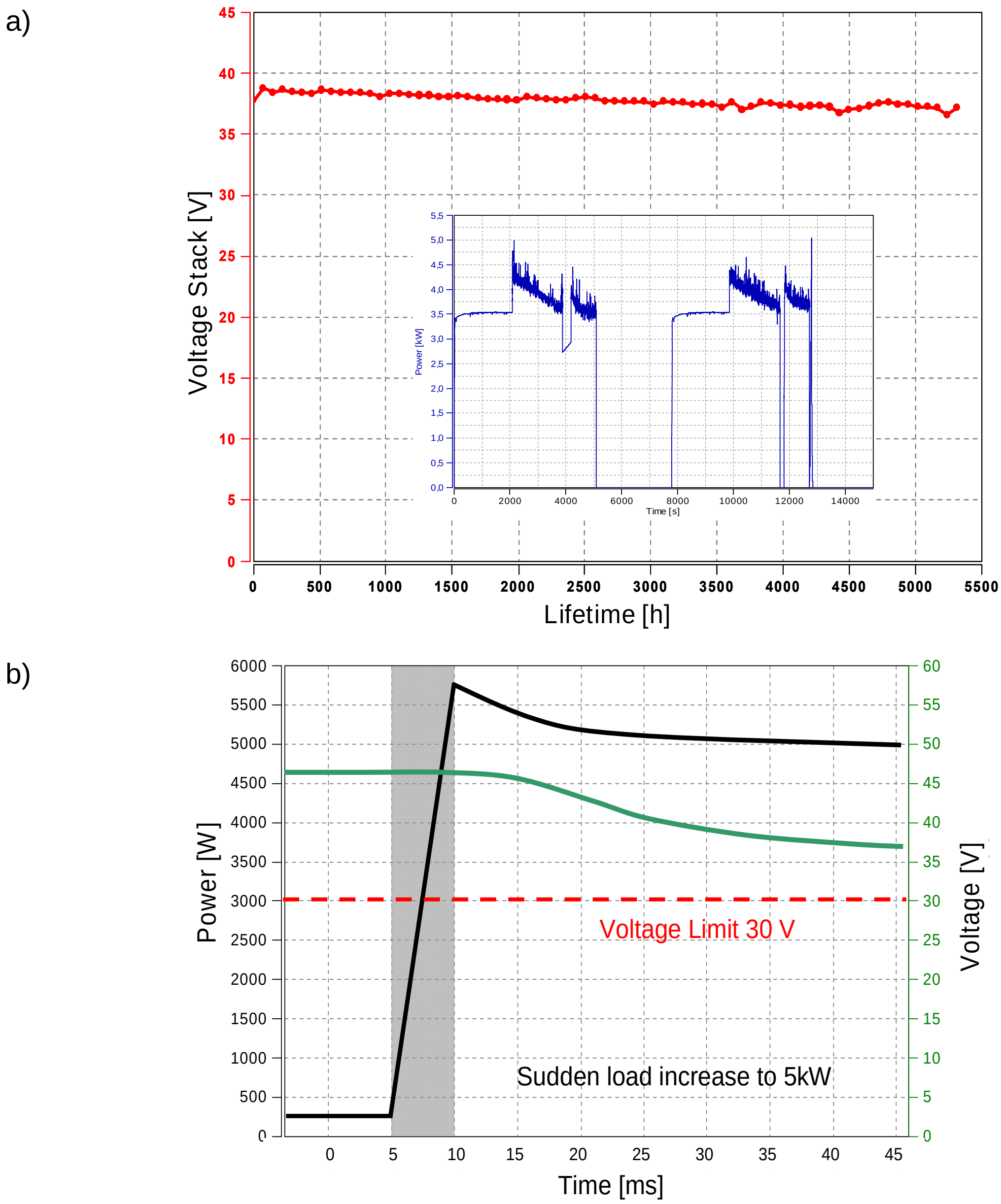



**Figure 3: APU relevant test cycles a) Load profile b) Transient response.**

With the help of water diffusion and evaporation of the water within the stack, an internal cooling system is also possible. This means no additional cooling circuit with a full flow cooling pump is necessary. A small pump, providing a slight vacuum pressure on the cooling water against the hydrostatic pressure is necessary. To reach a positive water balanced system at up to 60 °C, a condenser extracts the water from the cathode exhaust. If the system shutdowns, the water will flow naturally (with the help of gravity) to a reservoir. The complexity of the system is dramatically reduced. As a result, robustness and low cost are achievable.

## 3 Freeze Capability

The major challenge for mobile fuel cell applications is the cold start up at temperatures below 0 °C. In this case, the cooling water is completely frozen if the fuel cell is exposed to cold surrounding temperatures for more than one day.

The porous bipolar plates hold a small amount of water in the stack, which is sufficient to ensure the humidification of the reactants at the start initiation. This means no additional, external humidification is necessary. The system is able to deliver power to the vehicle 30 seconds after start-up. A certain amount of power is used internally to melt ice in the water reservoir at the bottom of the fuel cell system. This water is used for cooling and humidification when the system is heated up to normal operating temperatures.

In diagram 4, the voltage at different load levels during a period of 200 freeze start tests is shown. Only marginal changes in the fuel cell behavior after the tests indicate a very robust system under freeze conditions.

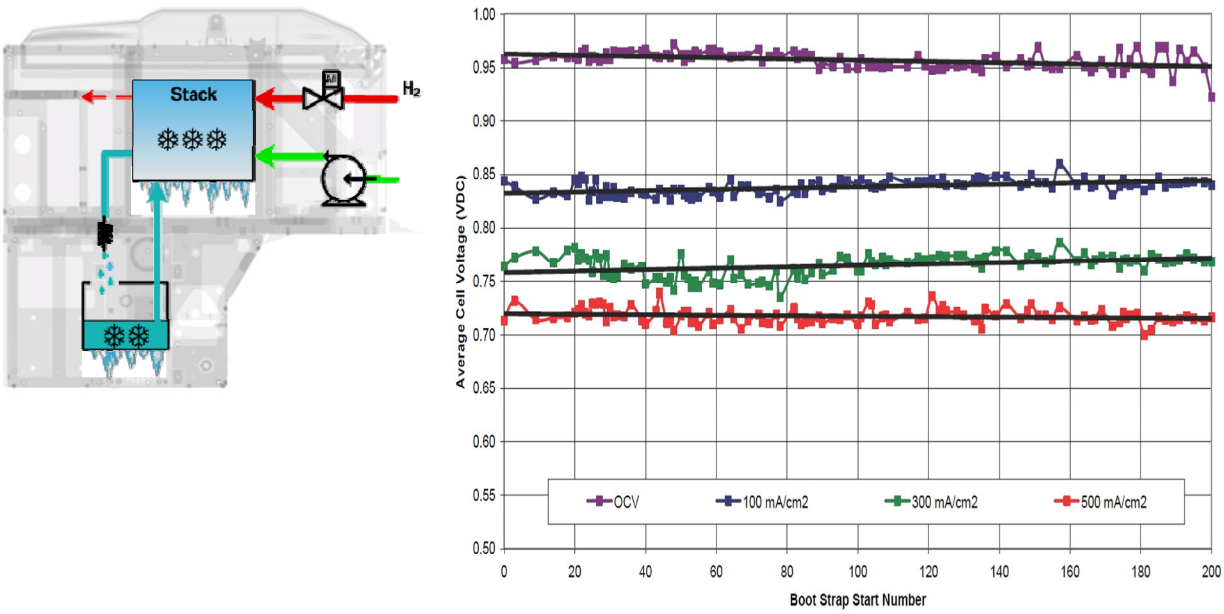



**Figure 4: Scheme of the Fuel cell at freeze conditions and cell voltage during 200 starts.**

Beside the lifetime investigation, startup tests with inclined systems are performed at the test stand. Testing the fuel cell with a maximum tilt angle of 17° in two directions (pitch and roll) should discover possible areas affected by ice blockage. These angles simulate extreme parking and freeze start positions. Figure 5 shows the frozen stack and the tilted freeze start with the climate chamber at the BMW test facility.

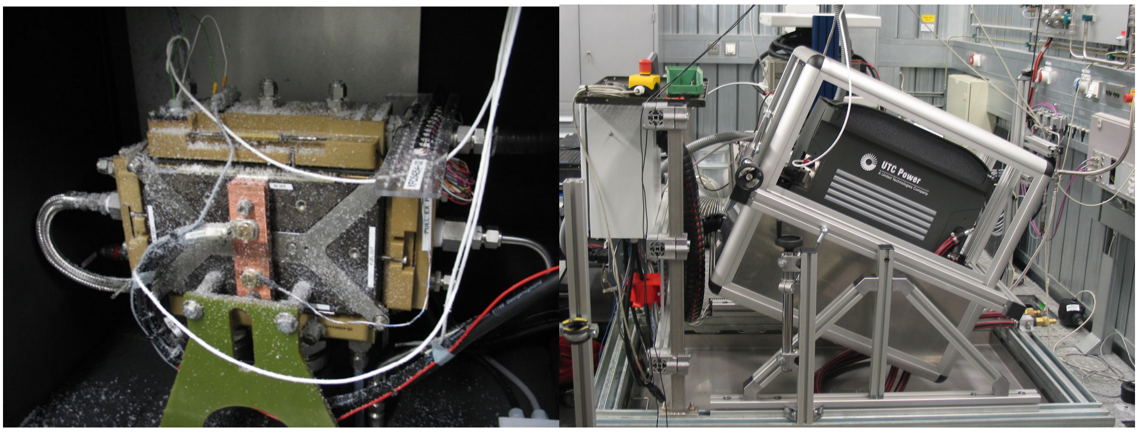



**Figure 5: Freeze test of stack and system with vehicle relevant load profiles.**

## 4 Fuel Cell Hybrid Car

The next step of the APU application in vehicles will be at BMW to supply power to the drive train at low speed. This concept allows driving without any emissions in urban and suburban areas. Based on analysis of the urban drive cycle, which is shown in Figure 6, only a power of approximately 3 kW is necessary to drive the vehicle during the whole cycle. With replacement of the alternator, in summary a power of 5 kW depending on the vehicle (e.g. weight, air resistance…) is required during the cycle. This average power and the supply of the 12 V board net can be handled with a very small fuel cell. Due to the low power output, an energy storage system is also needed to ensure acceleration and short driving periods at high speed (e.g. overtaking). With the use of the super capacitors, a recovery of the braking energy at deceleration is possible. This recuperation saves energy in the drive cycle and reduces fuel consumption.

The drive train of the 1-series car consists of one branch with a front wheel drive powered by the internal combustion engine. A second branch with a small fuel cell, super-capacitor and electric engine drives the rear axle. To charge the energy storage and for feeding the electrical engine, a DC/DC converter is necessary to shift the voltage from the fuel cell level to the drive voltage potential. Figure 7 shows the package of the car. With the shown arrangement of the components, the concept offers no significant customer disadvantages in case of space and payload.

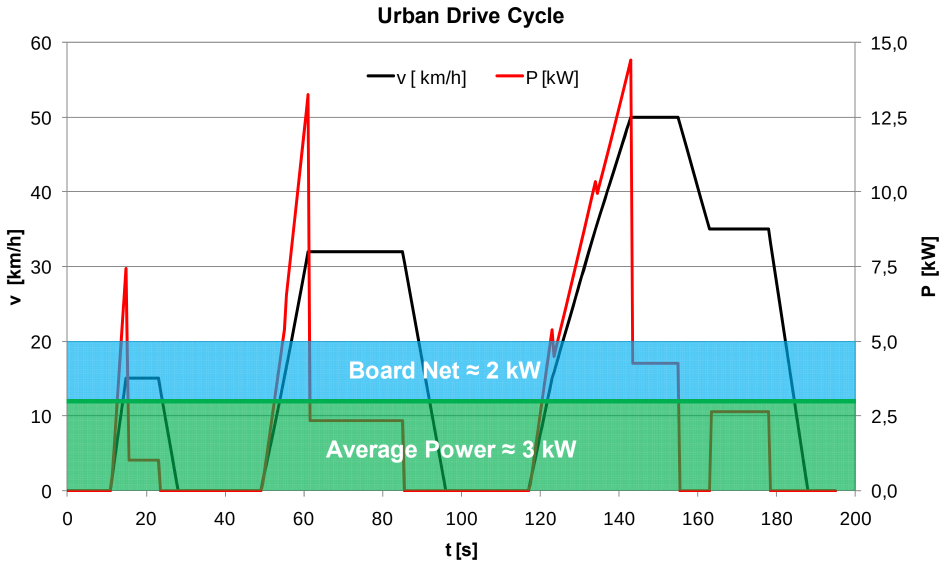



**Figure 6: Urban Drive Cycle and average power.**

The electric power train is designed to reach the highest efficiency in an urban drive cycle. Fuel consumption lower than 1 kg hydrogen per 100 km was measured at the dynamometer test stand with the vehicle undergoing the urban city cycle. Several city drives at warm and winter conditions confirm also these measurements. Driving at higher speed or at longer uphill distances, the internal combustion engine is switched on to ensure the demand of higher power. The fuel cell acts in this case as a pure APU and also improves the efficiency of the IC Engine by supplying the board net.

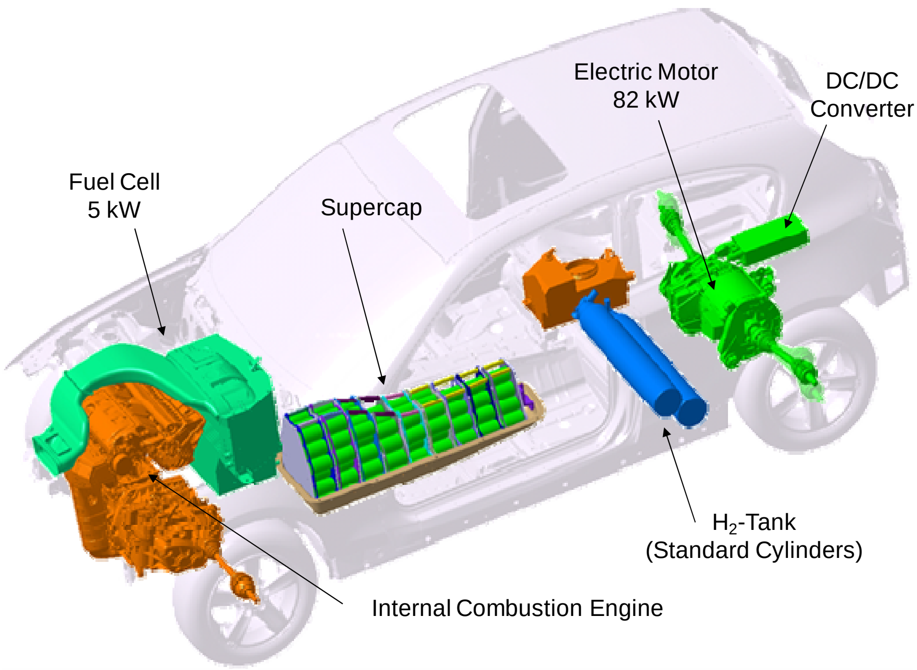



**Figure 7: Package of the 1-series, fuel cell hybrid car.**

According to this configuration, a vehicle concept is reasonable which ensures new customer benefits and allows driving without emissions in urban regions. During the introduction phase, the IC Engine can also be powered with gasoline or diesel. Hydrogen, supplied from the growing hydrogen infrastructure in cities can be used simultaneously with the two fuel vehicle concept. This technology has the potential to ensure the individual sustainable mobility in the future.

## 5 Summary

The developed APU system uses air and hydrogen at nearly ambient pressure and is designed for an electrical load of 5 kW. The high automotive requirements for lifetime and start up time at low temperatures are met without any significant degeneration of the system. With an immediate response from idle to full load, the APU offers an auspicious substitute to the electric generator and battery used today. Besides the higher efficiency compared to the alternator, the fuel cell can be operated independently from the internal combustion engine and therefore enables additional functionality for the customer e.g. air conditioning and office applications at standstill. In the car project, a zero emission vehicle was built up to demonstrate the feasibility to drive with only 5 kW APU power in urban areas. A maximum fuel consumption of 1 kg hydrogen per 100 km is feasible.

## References


[1] J. Tachtler, T. Dietsch, G. Götz: “Fuel cell auxiliary power unit – Innovation for the electric supply of passenger cars?”, SAE Technical Paper Series 2000-01- 0374, SAE 2000 World Congress, Detroit, 2000

[2] K. Pehr, S. Burckhardt, J. Koppi, T. Korn, P. Partsch: “Hydrogen– the fuel of the future – The BMW 750hL”, ATZ, 2002

[3] A. Schüers, A. Abel, C. Fickel, M. Preis, R. Artmann: “12-Cylinder hydrogen engine in the BMW 750hL“, MTZ, 2002

[4] M. Schneider, G. Götz, B. Fleming: “PEM fuel cell systems in automotive vehicles – the auxiliary electric power unit of the future”, NHA conference, 2004

[5] S. Friedmann, C. Jones, R D Mesiti, M. André, P. Carminot, M. Audient, A Künzer, N. Kyriakis: „Hybrid Vehicle Technology: A sustainable development for efficient zero emission mobility?” 6th international EAEC conference an “Lightweight and small cars- the answer to future needs”, Cernobbio, Italy 1997

# An Approach to the Precise Dosing of Fluids

**Axel Müller**, **Michael Gunkel**, **Horst Kappler**, **Thomas Rolland**, Thomas Magnete, Herdorf, Germany

### Abstract

Automotive dosing pumps have been available on the market for 25 years now. Initially used for fuel fired parking heaters in mobile systems – trucks, passenger cars e. g. –, this type of a reasonable dosing unit nowadays is applied in many fields. Based on the experience of delivering fuels, the dosing pump was advanced to deliver and admeasure more or less any kind of liquid media. One of the most innovative operational areas of such compact metering units is the fuel cell reformer technology, wherein a constant flow of a certain amount of fuel is desired.

This type of pumps combines the abilities of priming, delivering respectively metering of liquids, thus helping to optimize existent systems. Thanks to the characteristics of the compact dosing unit, complex hydraulic systems can be avoided. In contrast to separated systems for delivering fluids and metering them subsequently, the extensive integration of functions leads to less complex, more robust systems. Some components may become dispensable, such as sensors, shut-off valves or injectors. Thus, the amount of electrical and hydraulic interfaces may be reduced to the minimum, so that the total costs of the system become significantly lower.

Dosing units deliver fuel in a balanced manner. As they are designed as electromagnetically driven piston pumps, the piston is moved one to several times a second. The dosing pumps are able to pump a certain, small volume per stroke. Hence, based on this accurate volume, the total flow rate is determined by the frequency of the piston's movement only, which is the basis for easy control. This advantage, i. e. precise metering, is paid for with the disadvantage of the pulsing flow which is due to the principle of a piston pump. Current investigations into the flow characteristics show the significant potential which lies in the combination both principles: constant flow and precise metering. This effect can be achieved by designing the pump adequately or by using integrated attenuators. Based on relevant test results, potential influence factors, as counter pressure, temperature etc., are investigated into, too.

## 1 Introduction in Metering Units

Integrated piston-pumps for dosing fuel have been developed and manufactured in serial production for 25 years. Thomas started with the development and production in the mid-80s with the model "DP2". By using a special design of pump and actuator, the design of the "P450" is especially accentuated to this intention by reducing the stroke volume and the integration of an attenuator. Thus, the remaining pressure pulses are reduced over a wide range of temperatures, even with very low temperatures, so that they are not noticeable by the system. A second type series was initiated by Thomas Magnete in the early 1990s by developing the "P320" for heaters operated with Diesel fuels for Truck applications. In serial production since 1995, this original field of application was expanded and the “P320” soon became a basic dosing pump for several applications. This type is characterized by the robust design that simplifies the structure. Exceeding the ordinary arrangements for amelioration of serial products, the spectrum of power was extended significantly without enlarging the outer dimensions. The “P900” is a serial pump, specifically developed for aggressive and potential future fuels. Based on this, the prototype dosing units “P920” resp. “P923” are representing a new generation of pumps with an optimized design characterized by significantly smaller dimensions. Nevertheless, the performance of these prototypes is kept on the same high level or even meliorated.

Based on this, these types of dosing pumps are used for further applications. Prior to the year 2000, the use of the metering pumps using a piston pump-principle, was limited to the market for fuel operated heaters for mobile applications mainly. Since then, the specialized skills combined within these dosing pumps have been: priming, sucking, delivering, dosing/metering e. g. They enlarged the range of applications and enabled the optimization of existent facilities. Thanks to the sum of attributes, the compact dosing unit enables the designers to renounce complex, pressure-controlled metering systems. The widely advanced integration of functions and abilities makes many components dispensable. In contrast to separated systems for dosing and delivering liquids, expensive components as sensors, shut-off valves and injectors which have to be integrated costly, are not necessarily needed. By doing so, the total amount of electric and hydraulic and mechanical interfaces can be reduced to the minimum. This will lead to significantly reduced total weight, installation space, simplified fuel lines and total costs.

Auxiliary power units (APU) using fuel cells mostly need fuels in a special condition. Liquid hydrocarbons have to be converted into a gas mixture containing hydrogen by using a reformer. Trucks, aircrafts and cars usually have liquid fuels, Diesel e. g., aboard which have to be reformed before entering the fuel cell [5]. Hence, compact construction of the APU and the individual components and low weight are a necessity. According to [2], these systems may use Solid Oxide Fuel Cell (SOFC) technology. Such APUs are advantageous with regard to engine-independent availability of electrical functions, especially if highly integrated components are installed which fulfil all functions that are needed. Integrated shut-off valves guarantee safety under all critical situations, as no fuel can drop out of the fuel supply system. A valve at the outlet prevents gas from getting into the pump and the fuel supply system.

## 2 Mode of Operation

A solenoid driven actuator moves the metering system. Fig. 1 shows the actuator in a sectional view in normal position, i. e. not energized. Actuated by the solenoid, the pump’s piston is alternatingly being towed axially in the pump’s cylinder from the one end position to the other. The fluid is sucked into the pump through the filter by passing the sealing element. This sealing element is one of the safety features as it prevents medium from flowing backwards in case of a not-energized passive state of the metering unit. Subsequently, the fluid flows along the surface of the armature and pours into the cross-hole of the pump’s cylinder and then into the pump volume. This pump volume determines precisely the amount of the fluid which is emitted by each stroke of the dosing pump. In doing so, the fluid is passing another sealing element and the valve at the outlet, i. e. the pressure face.

The drive mechanism of the dosing unit operates by means of an electromagnet. By energizing the coil, the magnetic field establishes in the ferromagnetic circuit, see [1]. As the action of force is based on the ambition of the magnetic field to close the air gap between the pole and the armature, the slidable armature is moved in axial direction. Fig. 1 shows this air gap with the cone-shaped geometry. After switching off the voltage, the armature and the piston are towed back by the spring and achieve the normal end position again.

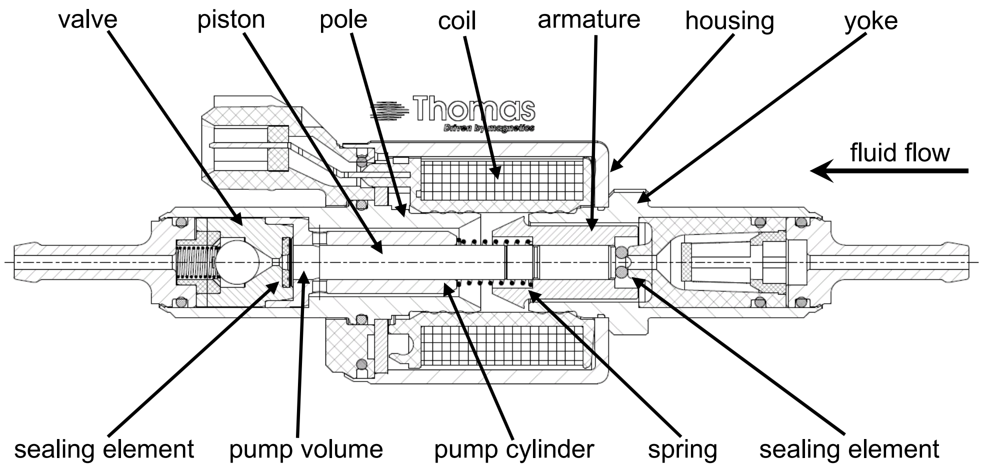



**Figure 1: „P325“ sectional view, non-energized, normal position shown.**

By applying the electric signal, the fluid is pushed through the thereby opened ball valve. Coming back to the normal end position, the pump can suck a further amount of fluid, as the ball valve at the outlet side closes and low pressure is generated within the pump volume. Once the piston passes the cross hole, further fluid can stream into that volume. With each electric pulse and depending on the control strategy, this sequence can be performed several times per second, each stroke emitting a fixed and exact volume. Thus, by controlling the driving clock frequency, the total amount of the metered fluid is ascertained.

## 3 Precise Fuel Delivery

As the precise flow rate is characterized by the exactly defined volume emitted per stroke, the clock frequency determines the total flow per time period. The graph shown in fig. 2 illustrates this linear correlation for two types of dosing units: high flow (“P325”; “P920”) and low flow metering pumps (“P450”; “P923”). Three parts of each type have been measured for this graph. Due to the fact that all these lines are lying upon each other, the excellent accuracy becomes obvious.

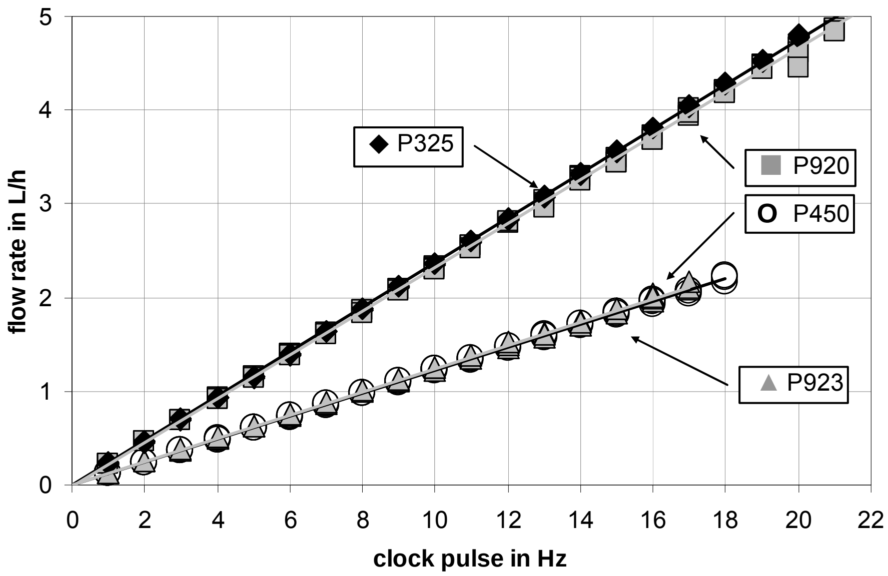



**Figure 2: Characteristic curve: flow rate versus clock pulse.**

For the investigation of the flow rate as a function of the clock frequency, the test set-up was chosen as follows: Each pump was actuated with a fixed voltage U = 12 V and the pulse width fixed at $t_{ON}$ = 25 ms at ambient temperature. ARAL 4005 has been chosen for testing, as it represents a not-flammable liquid hydrocarbon. This fluid was sucked out of a beaker placed on a scale. The pump under test was positioned horizontally and adapted with an outlet line leading in a separate canister under atmospheric pressure condition. Each measurement run consisted of 100 individual shots performed with constant clock frequency. The flow rate, shown in fig. 2, is the averaged value of these shots, resulting from the mass difference recorded by the scale.

The fuel volume delivered by one single shot of the pump was determined. The pump under test was actuated for one stroke of the piston and sucked the test fluid out of a beaker, which was placed on a scale. The mass difference before and after the pump actuation was the base for the delivered volume per stroke V. The pump was operated with a low frequency f = 0.5 Hz [low flow pump] or f = 1.0 Hz [high flow pump], respectively, the voltage was U = 12 V with a pulse width of $t_{ON}$ = 25 ms. The relevant data like the voltage U, the current I, the outlet pressure $p_{out}$ and the mass of the test fluid $m_{Fluid}$ was recorded continuously. All dosing units show a perfect accuracy from “shot to shot” with a standard deviation significantly less than 1 %. In absolute numbers, the volume delivered per stroke can be compared to a raindrop. According to literature [4], a typical raindrop is assumed to be in the size of 40 to 50 mm³ corresponding to the dimension of the delivered volume per stroke. Hence, the accuracy achieved has to be compared to one-hundredth of one raindrop only!

For a large number of applications, the average flow rate of several single shots is much more relevant than the consideration of one single shot. Each pump was actuated for 100 shots and the mass difference before starting the pump and after 100 shots was evaluated. By this method, the operation parameters of the pump could be modified in certain ranges. In Fig. 3, the measurement results for the different pump types, operated under the parameters – U = 12 V, $t_{ON}$ = 25 ms, f = 10 Hz, $p_{out}$ = 0 bar, are shown by presenting the difference of the averaged flow rate of 100 shots relative to the mean value of 200 repeated measurements. When regarding the average flow rate, the accuracy of the pumps is even significantly better than that of single shots. In field applications usually the averaged results should be considered for the layout of the corresponding system. The standard deviation of the metering pumps “P325” and “P450” was calculated with 0.15 % and does not exceed 0.31 %. Thus, the accuracy of the “average flow rate”, representing the main requirement for most field applications, is found to be at an excellent level.

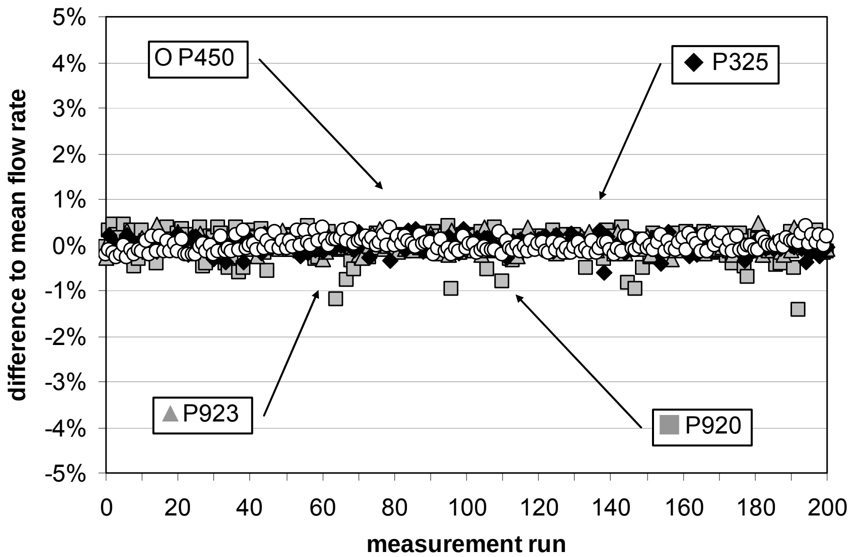



**Figure 3: Accuracy of the averaged flow rate over 200 measurement runs, 100 shots each.**

## 4 Precise Dosing Over Lifetime

Dosing units have to deliver the precise dosing during their lifetime. Hence, all pump designs were consequently tested in durability tests with different kinds of fuel, even Biodiesel-fuels containing aggressive substances. The global usage of metering units of that type requires robust designs and robust materials as they are in direct contact to the fluids. Well known for robustness, Thomas metering pumps available at the moment, are able to deliver all fuels that are commercially obtainable. For the future, investigations have been made to fulfil special demands for biomass fuels that potentially may degenerate. For that intention, test fuels have been used representing absolute worst case conditions, e. g. fuel blends like FAME containing water-, acid- and peroxide fractions. These test fuels are chemicals which are partly not available fuels and have to composed especially for these investigations. For example, the pump type “P320” ran in a durability test with ULSD (ultra low sulphur diesel) for a period time of 13,500 hours, actuated with a high frequency of f = 20 Hz. At the end of this durability test, approx. 1,000 million cycles, the deviation of the measured flow rate was less than 1.5 % relative to the nominal value. After dismantling the single parts of the pumps, every single part appeared like new, only minimal traces of use were recognizable. With the pump type “P900”, a durability test with aggressive diesel containing 20 % FAME, see [3], was performed at a temperature of $T_{Fluid} = T_{amb} > 50$ °C. The duration was 1,000 hours with a driving clock frequency of 17 Hz, i. e. 61 million cycles. The deviation of the measured flow rate after completion of the durability test was insignificant. All single parts of the pumps did not show any significant wear and have been found comparable to an unused condition.

## 5 Concluding Remarks

Excellent precision in metering characterizes the in-line dosing units. This precision is almost independent of the counter pressure and is guarantied for lifetime. Even a hypothetical chemical fluid, regarded to be the world’s worst fuel, was tested without harmful effects. After 1,000 h testing, the parts appeared like new. Also, a test for 13,500 h showed no degradation effects. Investigations into this bared an accuracy of considerably less than 1 % deviation from the mean flow. The averages of a preassigned number of strokes show even better results of less than 0.2 %. In addition to the accuracy, these in-line pumps show further special characteristics like self priming, robust design, high protection class and seal protection, high variability with regard to hydraulic and electric connectors. They are maintenance-free and designed for vehicle-lifetime as well.

For the usage within fuel cell systems and especially for the fuel delivery into reformers, Thomas metering pumps offer an integrated solution. No additional components, shut-off valves e. g., are necessarily needed. Thus, they offer a cost-effective solution ready for the market as 25 years of development and series production verify.

## References

[1] Kallenbach, E. et al.: Elektromagnete III 2008, Wiesbaden.

[2] Zizelman, J. et al.: Auxiliary Power Units with Solid Oxide Fuel Cell Technology for Independent Electric Power Supply in Passenger Cars, in: Fuel Cell World Proceedings 2002, pp. 306.

[3] Müller, A. et al.: Dosierpumpen: Neue Potentiale im Spannungsfeld zwischen Komfort und weltweiter Standardisierung, in: Hofhaus, J. (Ed.): PKW-Klimatisierung VI, 2010, pp. 174.

[4] Tabellen für die Rezeptur, Tropfentabelle DAC 2006.

[5] Peters, R.: Auxiliary Power Units for Light-Duty Vehicles, Truck, Ships and Airplanes, in: Stolten, D.: Hydrogen and Fuel Cells 2010, Weinheim.

SM Existing and Emerging Markets
SM.1 Off-Grid Power Supply and Premium Power Generation
SM.2 Space and Aeronautic Applications
SM.3 APUs for Road Vehicles, Ships and Airplanes
SM.4 Portable Applications and Light Traction

# Portable Applications and Light Traction

Jürgen Garche

**Abstract**

It is reported about low-power FC systems (< 250 W) and high-power systems (< 5 kW) for portable applications and light tractions. Based on the application it is derived the demand on fuel cells. For portable applications and light traction PEMFCS; direct liquid fuel cells (mainly DMFC) and SOFCs are discussed. Furthermore about the fuel supply is reported. Mainly liquid fuels are applied, which are used directly (alcohols, on ethanol, formic acid, sodium borohydride, dimethylether) or via reforming to H2-reach gases (alcohols, LPG). But also hydrogen is used stored in high-pressure cylinders or hydrides. The whole FC system (stack, gas processing, management system, and power conditioning) is described. Examples for portable power generators (500 W–5 kW) as backup power, grid-independent generators and auxiliary power units (APUs) are given. Also low-power portable applications are described in the ~25 W region (e.g. mobile and cordless phone, pagers, walkmans) and in the 25–250 W range (e.g., notebook, professional camcorder, toys). In the same way military applications are discussed, which have special requirements on the thermal and noise signature and the robustness of the systems. Because the power requirement of some special vehicles (e.g. scooters, motorbikes, forklifts, boats recreation vehicles) is in the range of the power of portable fuel cell, in this chapter are discussed also light traction applications.

# A Fuel Cell Driven Aircraft Baggage Tractor

**Stefan van Sterkenburg,** HAN University of Applied Sciences, The Netherlands
**Aart van Rijs, Huib Hupkens,** Silent Motor Company, The Netherlands

**Abstract**

Silent Motor Company and the HAN University of Applied Science collaborate in the development of an aircraft baggage tractor. The baggage tractor is equipped with an 8kW fuel cell stack connected to a 26kWh battery-pack.

The control system implemented minimizes the start-up time of the fuel cell system, protects the fuel cell against overload and underload and controls the State of Charge (SOC) of the battery to its optimum value. A practical SOC-determination method is implemented which does not need detailed knowledge about the batteries applied.

This paper presents a description of the fuel cell system, its energy management system and SOC-determination method and the results of first test measurements.

## 1 Introduction

Schiphol Group has formulated a strategy to improve air quality and reduce $CO_2$ emissions in its Sustainable Mobility Concept and Energy Blueprint. One of the cornerstones is to implement sustainable and green innovative technologies. Ground transport at Schiphol airport is responsible for 30% of all emissions and thus may contribute significantly to the objectives.

One of the current projects related to this is the testing of a fuel cell hybrid aircraft baggage tractor. Hybrid baggage tractors are used to transport baggage on the platforms outside as well as inside the cargo halls. The advantages a fuel cell system compared to the commonly used diesel generator are that a fuel cell system does not emit any exhaust fumes other than water, causes less noise, may be more efficient and doesn't have to be switched off when driving into the cargo halls. Figure 1 shows the baggage tractor under test.


**Figure 1: Hybrid aircraft baggage tractor equipped with a fuel cell system.**

## 2 System Description

The aircraft baggage tractor is a 3.3 ton hybrid Volk tow tractor, with a towing capacity of 8.5kW. It is equipped with a 12kW electric motor and 80V lead-acid battery-pack with a capacity of 320Ah.

The original diesel generator is replaced by an 8kW fuel cell system. The fuel cell system is constructed in such a way that it takes up the same space as the original diesel pack. Therefore, modifications to the tow tractor were limited.

The fuel cell system is composed of the following components:

- The fuel cell stack. The stack is produced by NedStack. It consists of 64 cells in series with a rated power of 8 kW and current of 250A.
- A 74 liter 350 bar hydrogen tank. A completely filled tank at ambient temperature contains 1.8kg of hydrogen, which represents a free Gibbs energy of 60kWh.
- A step-up DC/DC-converter which converts the fuel cell stack voltage to the 80V battery voltage. The converter is equipped with an input current control.
- Auxiliary equipment. This includes all hardware to make the fuel cell system operate such as equipment for the cooling system, air pump, pressure valves, extended safety facilities and the fuel cell control unit. The power consumption of all auxiliary hardware depends on the power delivered by the stack and varies from about 400W to 800W.
- The control unit. This unit controls all auxiliary equipment and the DC/DC-converter. An extended safety strategy and energy management system is implemented. Software is written in Matlab / Simulink and code is generated by the automatic code generation tool of Simulink.

## 3 Energy Management System

The main task of the energy management system (EMS) is to determine the power supplied by the fuel cell. In order to do so, a set of three control systems are implemented, which are active depending on the operational mode of the fuel cell.

At power up, a temperature based control strategy is followed. The current supplied by the fuel cell is adjusted to its maximum value, which depends on the temperature of the stack. This causes fast warming up of the stack and thus minimizes the starting up time of the fuel cell.

After starting up, the fuel cell system enters its operational mode. In this mode, the energy management strategy is based on a load following strategy combined with a SOC-maintaining strategy. This strategy is illustrated in figure 2.

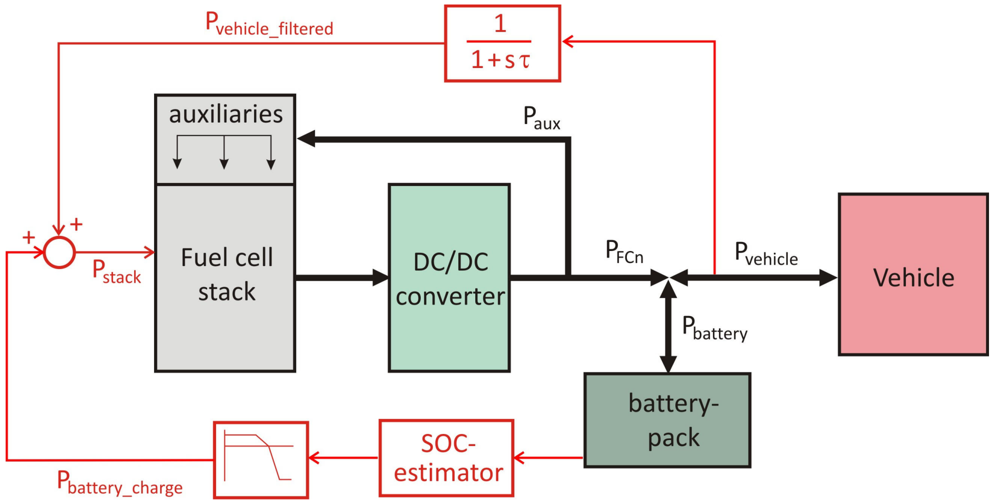



**Figure 2: Outline propulsion system with SOC maintaining EMS.**

The adjusted stack power is controlled to the following value:

$$P_{stack} = P_{vehicle\_filtered} + P_{battery\_demand}$$

The vehicle demand $P_{vehicle\_filtered}$ is determined by filtering the power consumed by the baggage tractor with a first order low-pass filter with a time constant of 10 seconds.

The battery demand of the battery $P_{battery\_demand}$ depends on the SOC of the battery and differentiates between four operating areas (see figure 3).

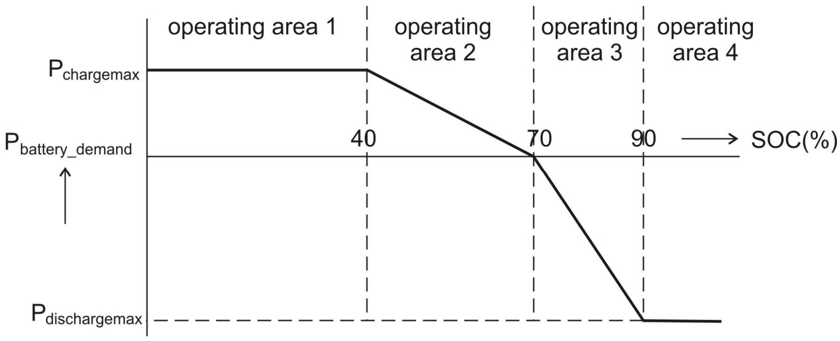



**Figure 3: Curve of power demand of battery-pack.**

Operating area 1: SOC<40%. In this operating area, the SOC is relative low, which is undesirable for reasons of increased deteriorating of the battery and the lack of sufficient buffer capacity in times of high power needs. To shorten the duration in this operating area, $P_{battery\_demand}$ is set to its maximum value. This value is determined by the maximum allowable charge current of the battery which is set to a C/3-rate charge current.

Operating area 2: 40% ≤ SOC < 70%. In this operating area the battery demand decreases linear from its maximum value to zero. The upper limit of this operating area (70%) sets the SOC point of operation because on average $P_{battery\_demenad}$ is zero in a steady state. A SOC operating point of 70% is chosen because this value is the best compromise between the following contrary requirements:

- A relative high SOC is favourable for the lifetime of the battery and lasting high power needs
- A relative high SOC causes less efficient charging of the battery [1] and may lead to more on and off switching of the fuel cell during idle periods of the baggage tractor.

Operating area 3: 70% ≤ SOC < 90%: In this operating area, $P_{battery\_demand}$ decreases further to its maximum discharge power. Its value is determined by the maximum allowable discharge current of the battery, which is set to 1C.

Operating area 4: SOC>90%: In this operating area, $P_{battery\_demand}$ remains constant at its maximum discharge power.

A third control action is activated if the average cell voltage of the stack exceeds the operating range of 0.5V-0.8V per cell. In this case, a proportional-controller controls $P_{stack}$ to the following value:

$$P_{stack} = P_0 + k_i * \Delta U$$

with: $k_i$ = proportional constant (the value of $k_i$ depends on sign of $\Delta U$)

$\Delta U = U_{stack} - n_{stack} * 0.5V$ if $U_{stack} < n_{stack} * 0.5V$
$\Delta U = 0$ if $n_{stack} * 0.5V < U_{stack} < n_{stack} * 0.8V$
$\Delta U = U_{stack} - n_{stack} * 0.8V$ if $U_{stack} > n_{stack} * 0.8V$
$P_0$ = value of $P_{stack}$ at the moment of activating this control action
$n_{nstack}$ = number of cells of the stack)

The current control of the DC/DC-converter controls the stack current $I_{stack}$ to a value of: $I_{stack} = P_{stack}/U_{stack}$.

## 4 Determination of SOC

The SOC is an important parameter in the energy management system. To determine it, several methods have been proposed in literature [2]. Most of them are based on complex battery models which need detailed battery parameters which are not known of the batteries used in the baggage tractor. To overcome this problem, a simple SOC determination method is applied which uses a combination of SOC-estimation from the electromotive force (emf) and Coulomb counting.

The emf of the battery is estimated by using the Thevenin battery-model [3] shown in figure 4.

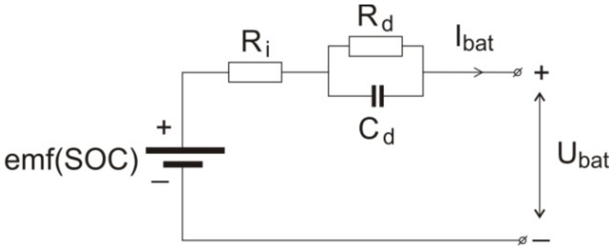



**Figure 4: Thevenin battery model.**

The internal resistance $R_i$ in this model is determined real-time by the difference equation:

$$R_i[n] = 0.99 * R_i[n-1] + 0.99 * \frac{-\Delta U_{bat}}{\Delta I_{bat}}$$

with $\Delta U_{bat}(t_i) = U_{bat}(t_i+2s) - U_{bat}(t_i)$ and $\Delta I_{bat}(t_i) = I_{bat}(t_i+2s) - I_{bat}(t_i)$

($t_i$ is the time sampled at a rate of 20 samples per second)

The calculation of $R_i[n]$ is only being executed when $|\Delta I_{bat}|$ exceeds 50A in order to prevent small measurement inaccuracies causing large errors.

All transient processes (charge transfer kinetics and diffusion processes) are represented by a single parallel circuit $R_d//C_d$. The values of $R_d$ an $C_d$ are determined empirically by analyzing the recovery of $U_{bat}$.

Based on the model above the emf voltage is determined from measurements of $U_{bat}$ and $I_{bat}$. From a lookup table, the SOC is then determined.

The accuracy of the SOC estimation from this method is rather limited at fast changing battery loads. This is caused by the simplified battery model that explains transients only with a first order approximation and inaccuracies in the determination of its parameters. Therefore, the SOC estimation of this model is filtered with a relatively large time constant of 300s to avoid fast fluctuations in the SOC caused by transient phenomena. The initial condition of the first order filter is set to 100% SOC. This prevents the battery to be overcharged at the start of a driving cycle when no accurate SOC estimation is available yet.

In order to determine the transient behavior of the SOC, also Coulomb counting is being applied. Coulomb counting is most effective to determine the changes in SOC in a short time interval. Deviations in current measurement and leak currents may cause drifting on the long term. For this reason, the SOC determined by Coulomb counting is filtered by a high pass filter. The same time constant is used as the low pass filter applied with the SOC-estimation from the emf. In this way both SOC-values can be added and a reliable value is obtained for both short term and long term.

## 5 First Test Results

At the moment of writing, the fuel cell driven baggage tractor is tested at short driving cycles of only a few minutes. These tests are primary meant to test the general working of the fuel cell system, to adjust any possible shortcomings and to get realistic values for the vehicle power demand.

Figure 4 shows the measured values of the vehicle current and charge current (the output current of the DC/DC-converter) and the SOC-estimation of such a test. The test has been executed at an ambient temperature of 12°C. The SOC of the battery-pack was about 50% at the start of the test.

From this measurement the following can be observed:

- At t=55s the fuel cell stack is turned on. The temperature based control strategy is then followed. About 240s later, the fuel cell stack has reached its operating temperature and switches to a load following / SOC maintain control strategy.
- The SOC starts with its initial value of 100% and drops with a time constant of 300s to its real value.

- In the time interval from 240s to 970s the vehicle is standing still and the power of the stack is determined by the SOC. The DCDC-converter charges the battery with a slowly decreasing current in order to charge the battery to its preferable value of 70%.
- From t=970s to 1125s the vehicle starts driving. The vehicle current varies roughly between 300A af full power and -100A at regenerative breaking. In this time interval, the current Icharge increases because of the load following strategy. The SOC-estimation shows a decreasing trend in this time interval. This must be explained by an inaccuracy of the SOC-estimation method.
- From t>1125s the vehicle is standing still again and the fuel cell stack further charges the battery to its preferable value of 70%.

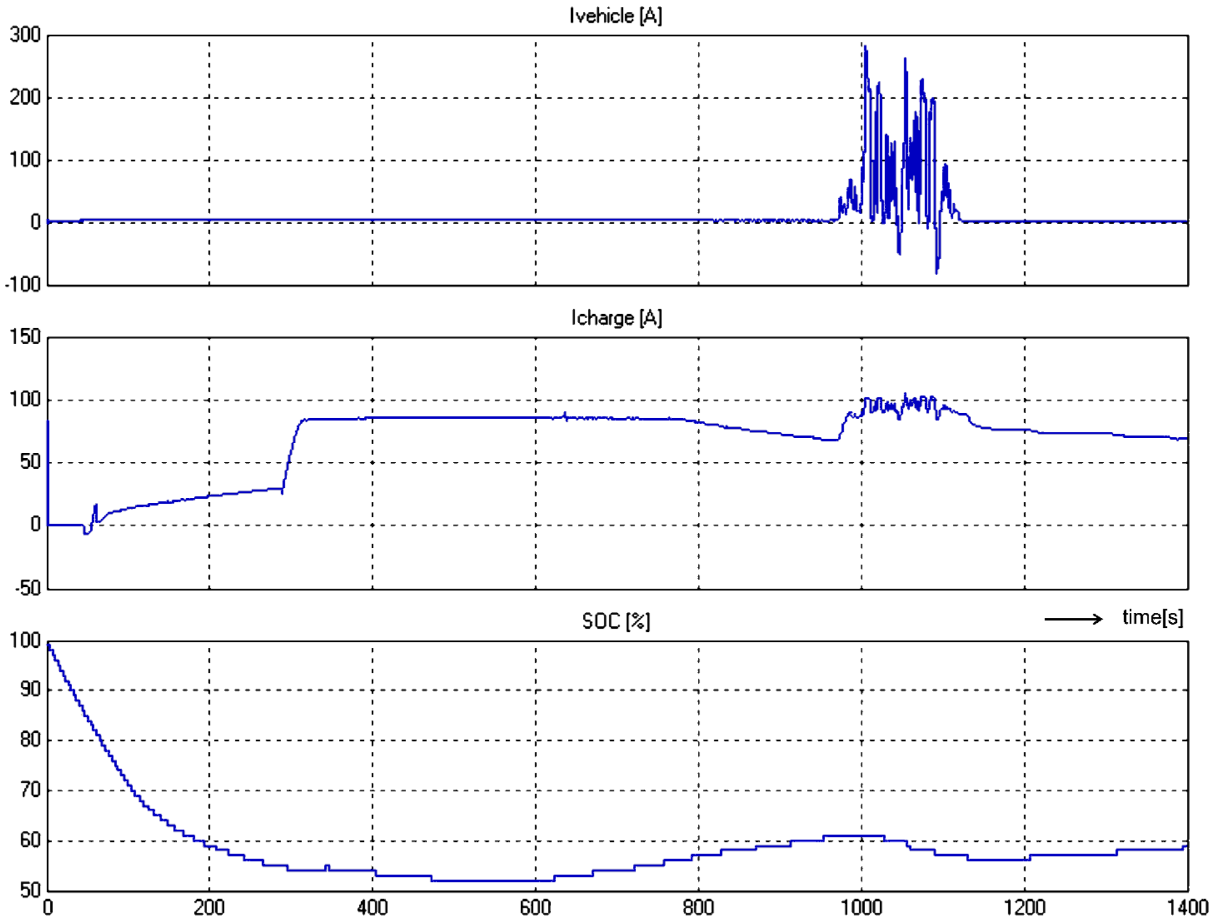



**Figure 4: The upper two graphs show the measured values of Ivehicle and Icharge. The lower graph shows the SOC-estimation.**

## 6 Conclusion

This paper describes the design of a fuel cell driven baggage tractor. Three control strategies are followed in the EMS: a temperature based strategy is active at starting up and takes care for fast warming op. The stack is fully operational within 4 minutes at an ambient temperature of 12$^{o}$C.

During normal operation, a load following / SOC maintaining strategy is followed. First test results demonstrate that this strategy works. The SOC-estimation method appears the most critical part of the strategy because of its inaccuracy.

The control strategy which adjusts the cell voltage within its operating area of 0.5V–0.8V is not tested yet.

## References

[1] J. Manwell and J. McGowan, “Lead acid battery storage model for hybrid energy systems, ”Solar Energy, vol. 50, pp. 399–405, 1993.

[2] “State-of-the-art of battery state-of-charge determination” by Pop, Bergveld, Notten en Regtien (Meas. Sci. Technol. 16 (2005) R93–R110

[3] “Dynamic model of a lead acid battery for use in a domestic fuel cell system”, M. Dürr, A. Cruden, S. Gair, J.R. McDonald, Journal of Power sources 161 (2006), pp 1400-1411

# System Technology Aspects for Light Traction Applications of Direct Methanol Fuel Cells

**H. Janßen**, **L. Blum**, **M. Hehemann**, **J. Mergel**, **D. Stolten**, Forschungszentrum Jülich GmbH, Germany

## 1 Introduction

Due to extended driving range and quick refuelling time the Direct Methanol Fuel Cell (DMFC) is advantageous for special niche applications compared to the traditional battery propulsion technology. The system setup is adapted to the boundary conditions of the particular unit. Usually there are guidelines for maximum space, weight and of course costs. Additionally technical rules are given concerning gaseous and noise emissions. Safety requirements for the electric drive system and the fuel must be fulfilled.

In this contribution the results of a system analysis on the basis of a first prototype system for the energy supply of a horizontal order picker (see Figure 1) will be discussed.


**Figure 1: Horizontal order picker (Jungheinrich AG, Germany), first prototype DMFC V3.1 of the energy supply system with DMFC technology.**

As reported two years ago [1] an industrial project was initiated to commercialize the DMFC technology for light traction as an alternative to battery systems. The first project phase focuses on technical R&D topics as performance enhancement and cost reduction, durability, water autonomous operation at elevated temperatures and packaging of sub components and development of prototypes.

## 2 Advances in the System Setup

The energy system of the horizontal order picker consists of a DMFC system hybridized with a battery. Setup and control of the energy fluxes within the active serial hybrid are described in [2].

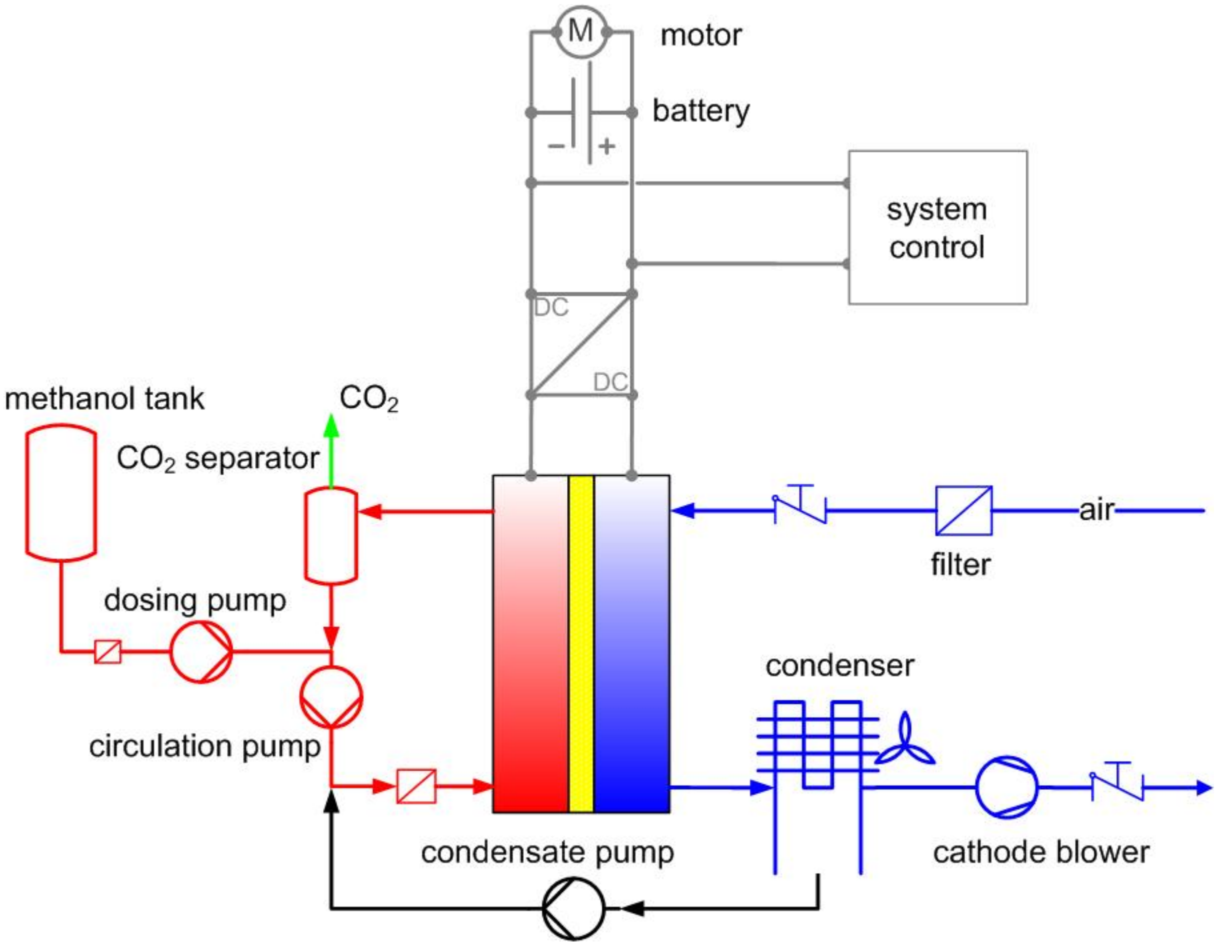



**Figure 2: Flow chart and basic electric setup.**

Figure 2 shows the general setup of the first prototype from Forschungszentrum Jülich called DMFC V3.1 (2007). The complexity of the DMFC system is quite low. Air and Methanol are the only operating fluids coming from outside the system boundary. The system operates at atmospheric pressure; the stack temperature is in the range 65...75 °C. Additionally the system consists of a closed water cycle. On the one hand water is consumed by the anode reaction and permeates through the membrane from the anode to the cathode side. On the other hand water is produced at the cathode side. By realizing internal water recycling a water autonomous operation is possible. Actually the water will be recovered by cooling the exhaust gas, condensing a part of the water content and pumping the liquid phase to the anode side.

The aim is to accommodate the complete energy system for the forklift truck in the battery tray. Figure 1 shows the implementation of the first DMFC V3.1 system. In addition to the main components DMFC stack (maximum power: approx. 1.5 kW), methanol tank (volume: 12 l, range: approx. 12 h), condenser (water autonomous up to an external temperature of 35 °C) and hybrid battery (capacity: approx. 1 kWh), a large amount of space was required for the electrical control system and data logging.

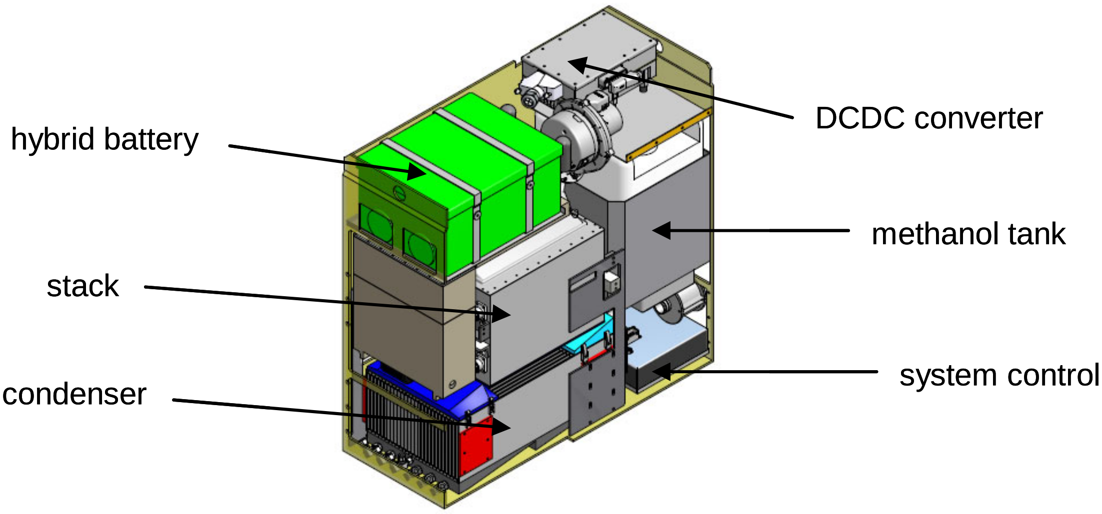



**Figure 3: CAD sketch of DMFC V3.3.**

The successor system DMFC V3.3 (see Figure 3, completed in 2009), which represents the further development of DMFC V3.1 in cooperation with an industrial consortium, comprises the following major changes:

- Increase in tank volume to 20 l. This brings us closer to achieving the goal of being able to operate a forklift truck for three full shifts in a warehouse on one full tank. This represents a significant advantage in comparison to conventional battery systems.
- Improvement in the temperature distribution in the battery tray. By means of a suitable air circulation system, the process heat created in the tray is directed to the outside.
- “Tailor-made” electronic components (control system with integrated data logging, DC/DC converter, cell voltage monitoring unit) developed for a compact setup.
- Concepts for reducing degradation in the stack when it is shut down (system for closing the cathode feed line, cyclical back-feeding of methanol).
- Improved control system and monitoring unit. The use of additional sensors for air mass flow, methanol concentration and temperatures should allow more robust and reliable system operation.

## 3 Heat and Water Management

In the actual system design DMFC V3.3 the rejected heat from the stack operation is transferred to the exhaust gas by water evaporation. This leads to a compact and simple system design, because no further cooling device on the anode side is needed. To cope with the heat extraction edge conditions regarding air and water quantities at the cathode side have to be fulfilled. The results from the thermodynamic calculations are shown in the following diagrams (Figure 4). By the definition of stacks with different power densities, the variation of the average cell voltage and the presetting of the fuel utilization a characteristic map of stacks regarding electrical and thermal economy can be calculated. In the first step the mass flow of evaporated water is determined whose energy content is equal to the energy content of the rejected heat. For different stack temperatures Figure 4 (left) shows the air/fuel ratio which is sufficient for the heat extraction according to the described concept. As an assumption the exhaust gas is fully saturated.

In the next step the condenser for the water recovery from the exhaust gas must be sized. The DMFC system is in water balance if the exhaust gas contains exactly the water coming from the inlet air humidity and from the methanol oxidation. In Figure 4 (right) the dewpoint temperature of the exhaust gas after the condenser is plotted against the air/fuel ratio.

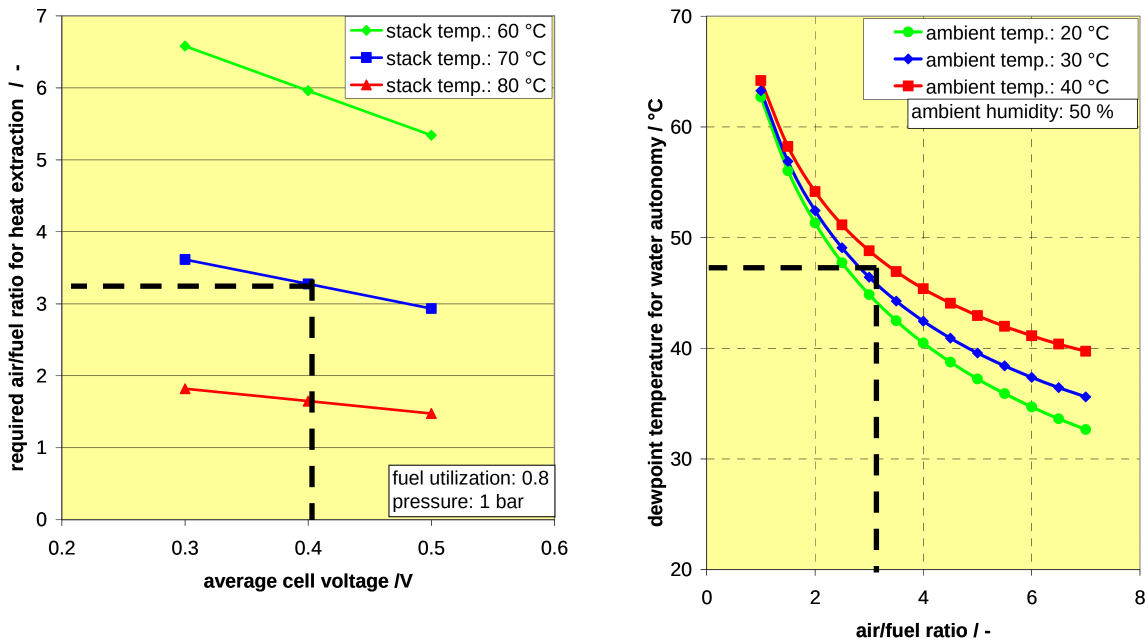



**Figure 4: Sizing diagrams for heat extraction and water recovery.**

The following Table 1 gives the sizing parameters for the condenser of DMFC V3.3. The dotted lines in Figure 4 represent the design point of stack and water management. Figure 5 shows the construction which is done in cooperation with AKG Thermotechnik, Germany. The condenser is made from stainless steel at the condensing side. Aluminium is used for the cooling fins. To minimize the condenser size the general setup is cross-counter-flow. That means the cooling air is directed horizontally from the left side to the right side through the cooling fins. The exhaust gas coming from the stack enters the condenser at the top side. Internally the exhaust gas will be deflected three times before it leaves the condenser via two pipes at the left top side.

**Table 1: Sizing parameters for the condenser.**

| | |
|---|---|
| Stack power | 1.3 kW |
| Air mass flow cathode | 23.2 kg/h (air/fuel ratio ~ 3) |
| Maximum exhaust gas inlet temperature condenser (~ stack temperature) | 70 °C |
| Maximum ambient temperature | 35 °C |
| Condenser outlet temperature for water autonomy | 47.5 °C (see Figure 4) |

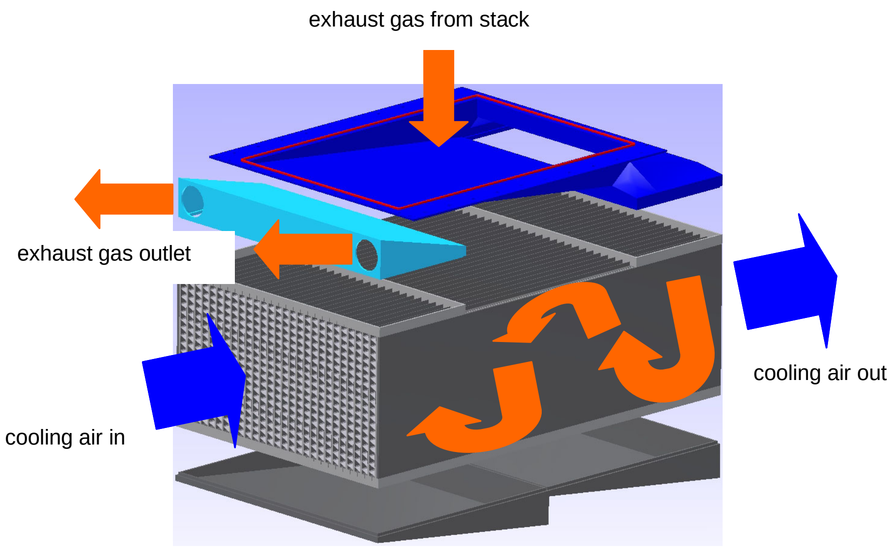



**Figure 5: Condenser design for DMFC V3.3.**

## 4 Stack Integrated Anode System

Main target of the new anode system development is the reduction of installation space for the complete DMFC system [3]. The packaging considers the integration of the system in a battery tray. In Figure 6 a cross-sectional view of the construction and the stack integration is shown. In addition to the main components like $CO_2$ separator and containers for level fluctuations of the anode fluid all actuators and sensors for the anode sub system are installed. The dotted line in Figure 6 represents the pathway of the anode gas (primary $CO_2$) beginning from the separator inlet to the condenser inlet which is located under this unit. For a better orientation the cross-section in Figure 6 is also shown as an isometric drawing.

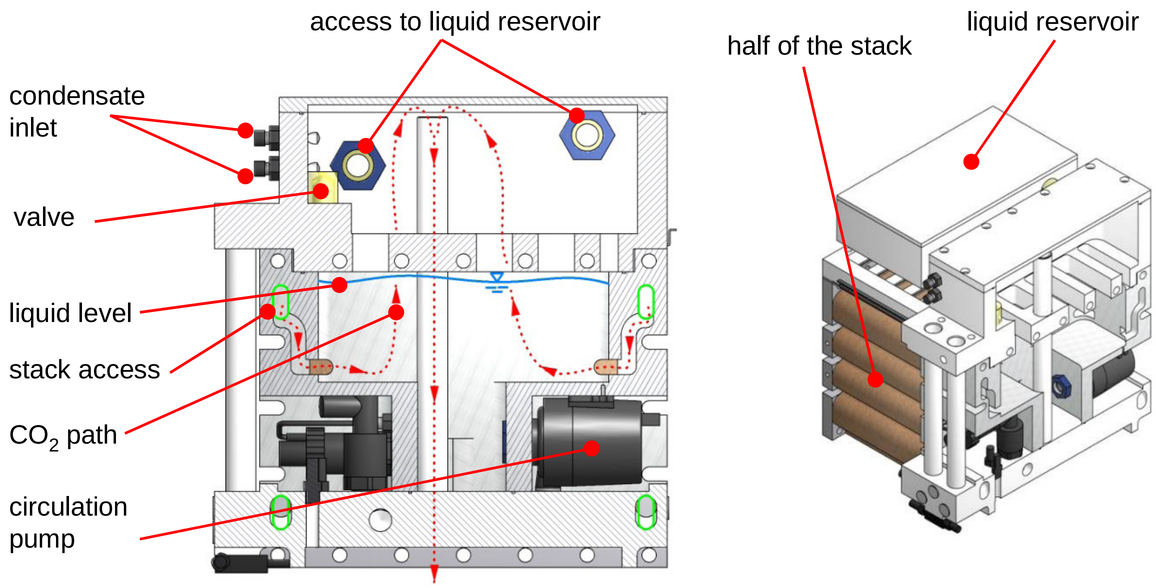



**Figure 6: Construction details of the stack integrated anode system.**

## 5 Conclusions

It could be demonstrated that it is possible to replace the original energy system of a horizontal order picker by a DMFC hybrid system without installation space modifications. There are lots of ideas for technical improvements which have the focus to increase the robustness and the advantages against battery systems, like operating time and operating costs.

### References

[1] M. Müller, H. Janßen, J. Wilhelm, J. Mergel, D. Stolten "Direct Methanol Fuel Cell Systems – An Option for Fork-lift Trucks" Proceedings of the 17th World Hydrogen Energy Conference, Brisbane, Australien, 15.-19.06.2008

[2] J. Wilhelm, H. Janßen, J. Mergel, D. Stolten "Horizontal Order Picker Driven by a Direct Methanol Fuel Cell" Symposium on Power Electronics, Electrical Drives, Automation and Motion 2008 (SPEEDAM 2008), Ischia (Italy), 11 – 13 June 2008, ISBN 978-1-4244-1663-9, pp. 832 – 836, http://dx.doi.org/10.1109/SPEEDHAM.2008.4581324

[3] M. Nölke: "Entwicklung, Auslegung und Umsetzung eines DMFC-Systems der kW-Klasse" PhD Thesis, RWTH Aachen University, 2007

# Development of a 100W PEM Fuel Cell Stack for Portable Applications

**Inci Eroglu**, **Serdar Erkan**, Middle East Technical University – Department of Chemical Engineering, Ankara, Turkey

**Abstract**

In this work, an air cooled 100W stack was designed, manufactured and tested. The bipolar plates were manufactured by CNC machining of graphite. Membrane electrode assemblies (MEAs) were produced by spraying catalyst ink onto the gas diffusion layer (GDL). A fuel cell stack was assembled with 20 cells each having 12.25 $cm^2$ active area. The test was carried out with $H_2$ at anode and air at cathode side both at 100% relative humidity having 1.2 and 2 stoichiometric ratios, respectively. The operating temperature of the stack was kept at 60$^oC$ during the test. The results indicated that the stack has a maximum power of 60W at 12V operation. Cell numbers 1, 2, 3 and 20 always had less potential than the 0.6V average cell voltage. Uniform cell voltage distribution has been achieved by improving thermal management and reactant distribution.

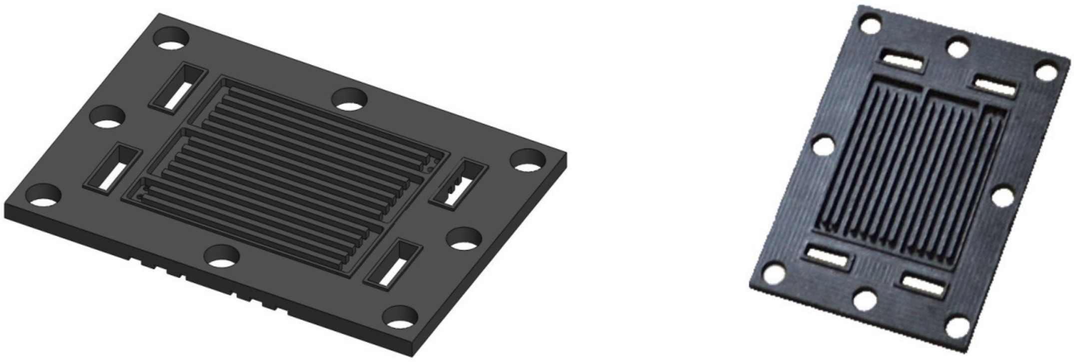
## 1 Introduction

Fuel cells are electricity generators which are converting chemical energy of hydrogen directly to electricity by means of electrochemical oxidation and reduction reactions. While the operation of them is similar to batteries without any mechanical parts, the electricity generation is continuous as the case in mechanical electricity generators. A single PEM fuel cell can only generate electricity with a potential between 0.5V and 1V. However, one needs more potential in order to utilize the electrical energy generated by fuel cell. The useful potential can be achieved by stacking cells in series to form a PEM fuel cell stack. However, water and heat management play important roles in bipolar stack performance [1]. The aim of this study is to design and manufacture an air/$H_2$ 100 W PEM fuel cell stack for portable applications.

## 2 Design of the Stack

### 2.1 Bipolar plates

Figure 1 shows the bipolar plate that was designed and manufactured by means of a CNC router in our lab. The active area of the plate was 12.25$cm^2$ and machined 300µm above the gasket area. The active area of the plates designed and manufactured having three parallel serpentine flow channels with lands are 1mm wide and 1mm depth.



(a) (b)

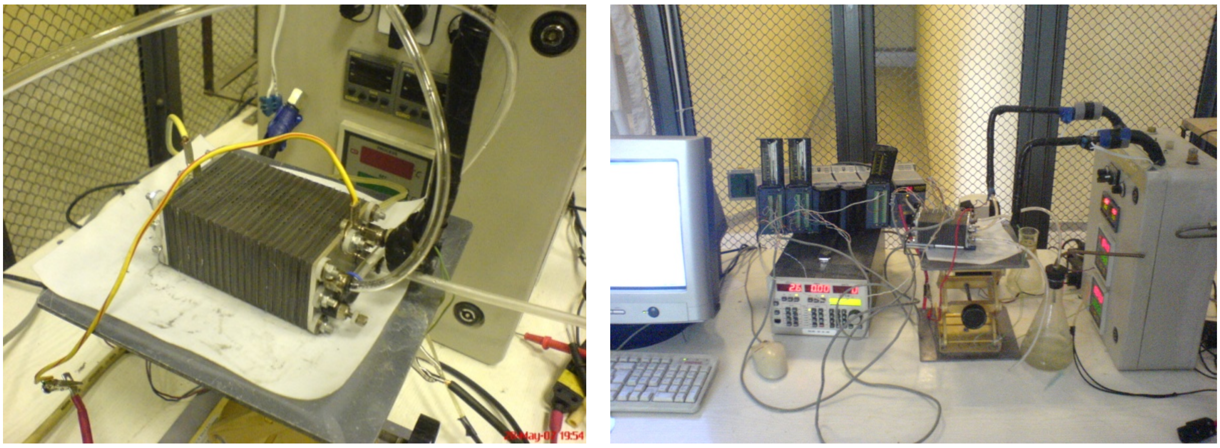
**Figure 1: Designed and machined graphite bipolar plate (a) CAD solid model (b) photograph of machined bipolar plate.**

### 2.2 MEAs used for the stack

The membrane electrode assembly (MEA) was prepared by spraying catalyst ink onto the gas diffusion layers (GDLs). The gas diffusion layer was GDL 31 BC type (SGL Carbon, Germany). The platinum loading was 0.4 mg Pt/cm$^2$, whereas Nafion® loading was 1.2 mg Nafion®/cm$^2$ in catalyst ink. After spraying the catalyst ink onto the gas diffusion layer a five layer MEA was prepared by pressing these GDLs onto the Nafion® 112 membrane (thickness: 50 µm) at 130$^o$C, 250 psi for 3 min [2,3].

### 2.3 Test station and performance tests

The fuel cell tests were performed in a homemade fuel cell test station which is shown in Figure 2. The test station is capable of testing single PEM fuel cells and small PEM fuel cell stacks. In order to access the required power, reactant gas flow rates were adjusted with mass flow controllers (Aalborg GFC 171). The flow rates for the anode and cathode were adjusted as having 1.2 and 2 stoichiometric ratio, respectively. Prior to entering the fuel cell stack, these gases were humidified to 100% relative humidity (RH) by passing them through the stainless steel humidifiers. The gas lines were heated to prevent the condensation of the water in the lines. The temperature in the humidifiers, the gas lines and the fuel cell were controlled by PID temperature controllers. The exhaust gases pass through water columns. The power of the stack was adjusted by an electronic load (Dynaload RBL488, TDI) that was controlled by a fuel cell testing software (FCPower). Voltage of the cells was monitored and logged by a cell voltage monitor system (Yokogawa MX100).



(a) (b)

**Figure 2: Photograph of (a) PEM fuel cell stack (b) the test station.**

## 3 Results and Discussion

The stack was assembled with 20 cells and the performance tested in the test station (Figure 2). The stack temperature was kept at 60$^o$C during the test. Figure 3 illustrates the cell voltage measured at each cell of the stack at OCV, 13V, and 12V of stack potential. Most of the cells have an open circuit voltage close to 1.1V. Whereas, four cells which are the first, second, third and the last cell have lower OCVs (0.84V – 0.97V) than the other cells. Stack OCV is 21 V. However, voltage drops was observed as expected when the stack is connected to an external load. When the stack voltage is adjusted to 13V, most of the cells have a potential above the average voltage (0.65V). The first, second, third and the last cells have lower voltage (0.45V - 0.56V) than the average voltage. When the stack voltage is adjusted to 12V, most of the cells are above the average cell voltage (0.6V). In parallel to the previous measurements the first, second, third and the last cells have lower voltage (0.36V - 0.48V) than the average voltage.

Figure 4 illustrates the polarization curve for the tested stack. The maximum power of the stack is 60W that is obtained at 11V and at a current 5.5A. The low performance of the first, second, third and twentieth cells decreases the design value (100W).

In Table 1, the results of the present study are compared with the published performance results of 12-220W hydrogen-air PEMFC short stacks and stacks. The power density obtained with short stacks is reported as 550-630mW/cm$^2$ [4, 5]. In the present study we achieved higher performance (250mW/cm$^2$) with stacks than the results of Jiang and Chu (2001) [1] (57-150mW/cm$^2$) and Urbani et al. (2007) [6] (80mW/cm$^2$).

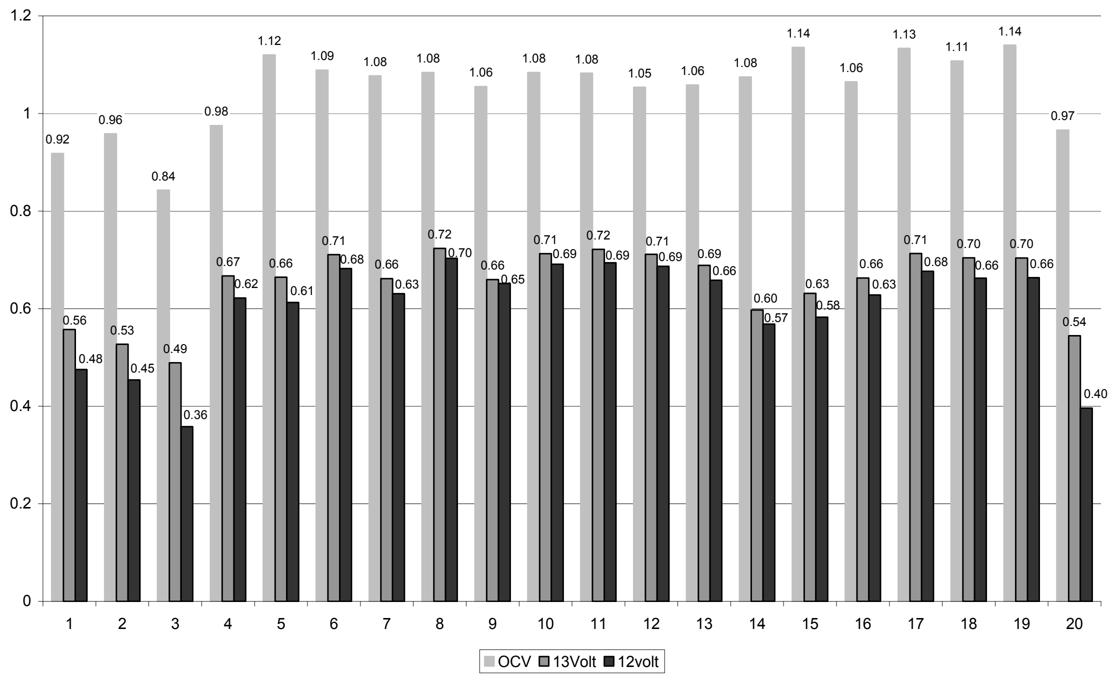



**Figure 3: Cell voltage distribution of the stack.**

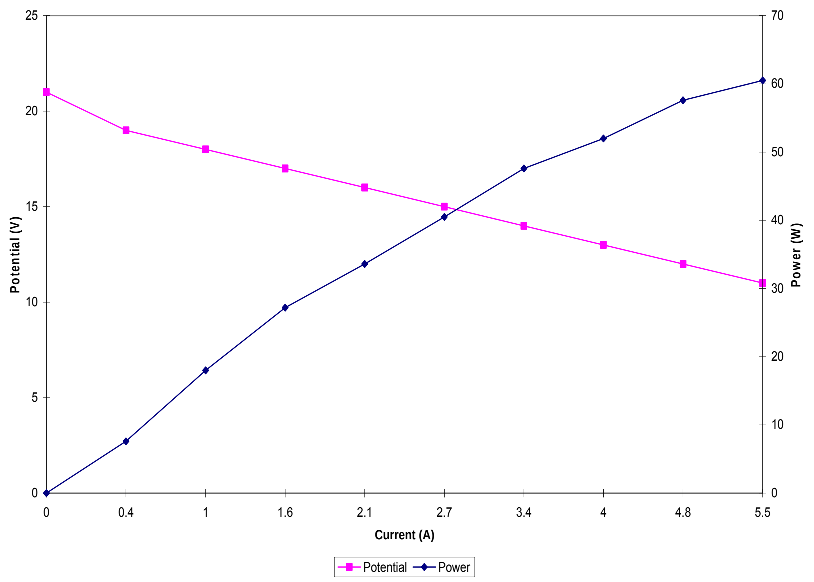



**Figure 4: Polarization curve for the tested stack.**

Knobbe et al. (2004) [4] achieved a 33% increase in power output of a PEMFC short stack by active gas management (AGM) system integrated by controlling the inlet and outlet of each cell individually. However, that is not applicable for real portable applications.

Weng et al. (2007) [5] developed a 200W short stack with four cells. They reported the maximum power densities of short stacks having 1, 2, or 4 cells as $0.55 Wcm^{-2}$, $0.48 Wcm^{-2}$ or $0.38 Wcm^{-2}$ respectively. They concluded that as the cell number increases, the uniform distribution of humidified gases, optimal moisture of membrane and gas diffusion layer to avoid the water flooding become significant.

**Table 1: Comparison of the published performance results of the 12-220W hydrogen-air PEMFC short stacks and stacks.**

| Stack Power (W) | Number of Cells | Active Area ($cm^2$) | Power density ($mW/cm^2$) | Reference | Year |
|---|---|---|---|---|---|
| 12 to 150 | 6 to 30 | 19 to 60 | 57 to 150 | Jiang and Chu | 2001 |
| 50 | 6 | 94.3 | 630 | Knobbe et.al. | 2004 |
| 20 | 10 | 25 | 80 | Urbani et.al. | 2007 |
| 220 | 4 | 100 | 380 | Weng et.al. | 2007 |
| 50 | 20 | 12.25 | 250 | Present study | 2010 |

## 4 Conclusion

Most of the cells operated at a potential higher than the average cell potential of 0.6V. The first three cells at the entrance and the last cell give a potential (0.36V - 0.48V) less than the average potential. The performance loss is most probably due to the thermal and reactant misdistribution. Uniform cell voltage distribution can be achieved by improving thermal management and reactant distribution.

Another reason might be due to differences in the performances of MEAs prepared by hand spraying. Therefore, it is recommended to improve the MEA preparation technique to produce MEAs having uniform thickness with identical catalyst load.

## References

[1] Jiang Rongzhong, Chu Deryn, “Stack design and performance of polymer electrolyte membrane fuel cells” Journal of Power Sources 93 (2001) 25-31.

[2] Bayrakceken, A., Erkan, S., Turker, L., Eroglu, I., “Effects of membrane electrode assembly components on proton exchange membrane fuel cell performance”, International Journal of Hydrogen Energy 33 (2008) 165-170.

[3] Şengül E., Erkan S., Eroğlu İ., Baç N.” Effect of Gas Diffusion Layer Characteristics and Addition of Pore Forming Agents on the Performance of Polymer Electrolyte Membrane Fuel Cells” Chemical Engineering Communications, 196, 1-2 (2009) 161-170.

[4] Knobbe M.W., He W., Chong P.Y., Nguyen T.V., “Active gas management for PEM fuel cell stacks”. J. Power Sources 138 (2004) 94–100.

[5] Weng Fang-Bor, Jou Bo-Shian, Su Ay, Chan Shih Hung, Chi Pei-Hung, “ Design, fabrication and performance analysis of a 200W PEM fuel cell short stack” Journal of Power Sources 171, 1 (2007) 179–185.

[6] Urbani F., Squadrito G., Barbera O., Giacoppo G., Passalacqua E., Zerbinati O., Vega-Leal Alfredo P., Palomo F. Rogelio, Barrag´an Felipe, Garc´ıa Covadonga, J. Brey Javier, ”Design of control systems for portable PEM fuel cells” Journal of Power Sources 169 (2007) 194–197.

# Sub Kilowatt Fuel Cell Systems – Solutions for Applications

**P. Beckhaus, S. Gößling, T. Notthoff, A. Heinzel,** Zentrum für BrennstoffzellenTechnik ZBT GmbH, Germany

## 1 Introduction

Development of fuel cell stacks and its components is a core topic for R&D and industry. Fuel cell development has to go hand in hand with optimisation of supplying peripheral components and controls. At ZBT the work is focussed on small PEM fuel cells (LT & HT) and their systems, specialising on stack and system development in the range between 100 W and 1.000 W, hydrogen or reformate powered.

Fuel cell systems in the sub kilowatt range serve numerous possible applications. With the described fuel cell stack technology system designs have been realized for different types of applications, eg.:

- Supplying electrical power for drives with high efficiencies of about 60 %,
- Supplying electrical power for small UPS devices with minimum startup times, very high power densities and wide range of tolerable environmental conditions
- Supplying oxygen reduced breathing air for simulated high altitude training of athletes
- Supplying autonomous electrical power for portable and leisure applications

In this paper the different strategies for exemplary system designs and controls are discussed and results of operation of the fuel cell stacks and the systems are presented. Focus of the development is always the solution for the application including all necessary testing routines for secure operation.

## 2 Fuel Cell Stack Technology

The fuel cell systems described within this paper are based on a hydrogen powered air cooled polymer electrolyte fuel cell stack (PEFC). The stack is a development of the research institute ZBT and is based on commercially available membrane electrode assemblies (MEA) and injection moulded graphite based bipolar plates with 50 $cm^2$ active area [1] [2], Figure 1. The core benefit of this plate production method is the significant reduction in the total production time for the plates and a constant high quality. Even at relatively small quantities of 500 plates the production process from raw material to pre-finished plate including flow fields and structures has been demonstrated to be less than 2 minutes per half-plate. This enables ZBT building up uniform stacks in sufficient volumes for R&D and demonstration purposes. The stack technology and the surrounding media supply and controls for various applications are available for power supply applications in the range of 200 $W_{el}$ up to 750 $W_{el}$ [3] [4] [5] if using air cooling. Systems using the liquid cooled stack setup can be constructed up to 1.2 $kW_{el}$. In Figure 2 exemplary the IV-curve of a 24 cell stack is shown.

**Figure 1: 24 cell air cooled fuel cell stack / ZBT.**

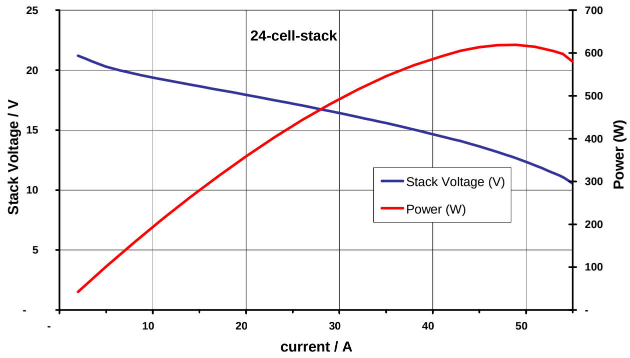



**Figure 2: Voltage and current characteristics of a 24 cell stack.**

## 3 Control Methodology

For fuel cell system setups a complex controller is needed to handle several system security requirements and for an optimal operation of the system. Simulation can be used to find the controller parameters and to test operation strategies. Interactions between the simulation and the real system are essential but complex. A close link between simulation and real system is important. The ZBT system simulation, programmed in Matlab/Simulink®, is divided into a model of the fuel cell system and a model of the controller. The controller model is enhanced with a blockset designed by Fraunhofer IIS [6]. It enables to generate the source code for the controller of the real fuel cell system, based on an “Atmega 128 microcontroller”. Blocks for “digital IO”, “analog in”, “pulse width modulation out”, RS232, SPI and I2C are added to the input and output. A master block is used to perform the necessary setup of the microcontroller. Finally the source code is build with the Simulink Real-Time Workshop® and is programmed directly to the microcontroller, Figure 3. This close relation allows an easy reciprocal enhancement of the real system, the simulation and the controller, Figure 4.

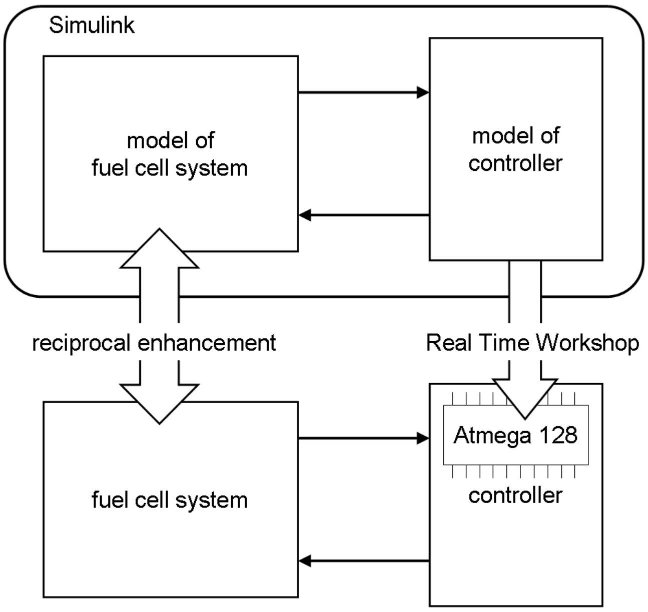



**Figure 3:** **Interaction of simulation and real system.**

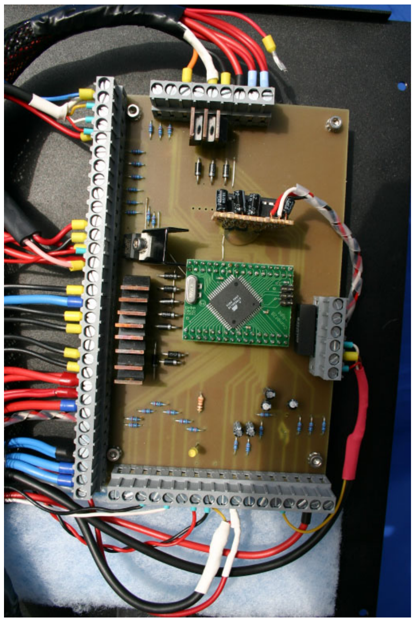


**Figure 4:** **Developed controller board.**

## 4 $H_2$ - Fuel Cell System Module

High efficiencies and low emissions make the fuel cell an interesting option for Auxiliary Power Units, APU. A couple of applications can take advantage of the short starting time and high dynamics of hydrogen powered fuel cell systems. Various system approaches have been designed for the special need of the specific application. The design of a modular system with very few and simple interfaces reduces that high effort to a minimum. The developed system (see Figure 5, 4) is based on the 19“ standard, the system support is reduced to a hydrogen supply connection and a 24 V voltage supply.

**Figure 5:** **Modular 500 W FC system.**

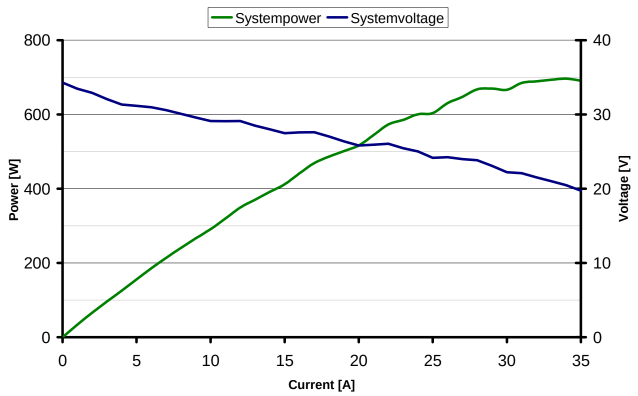



**Figure 6:** **System voltage and performance curve.**

The reason for the external supply of the necessary power for the peripheral components at 24 $V_{DC}$ is that thereby the system does not need any additional storage devices such as batteries. The module is integrated into existing energy architectures which usually have storage devices or any form of starting voltage available. During fuel cell system operation the peripheral power can be served by the fuel cell system itself.

On the other hand the used approach to give the stack terminal power directly as output of the system module is a result of the experience of various system design projects performed. The individual application normally needs a special power conditioning module eg. for charge control of used batteries, serving special load voltages etc. Therefore it was decided to exclude this part out of the main system module and thereby increase the final system efficiency. Surely the stack is protected against reverse currents and short circuits by electric components.

The system design enables furthermore online analyses like electro chemical impedance spectroscopy and current interrupt method.

The technical data of the system module can be summarized by this:

- overall size: 483 x 230 x 300 mm (l/w/x/h)
- weight: approx. 17 kg
- air cooled stack with 38 cells
- hydrogen (3.0) / 2 - 6 $bar_{abs}$
- power supply periphery: 24 $V_{DC}$
- output voltage: 20 V - 35 $V_{DC}$
- power: 500 W / max: 750 W
- environment: 4 °C - 30 °C
- start time approx. 2 sec.
- analog and digital port (RS232)
- CE – approved

The modular system design enables an easy integration in other systems. The 19” body fits perfectly for telecommunication purposes and building services. The system provides the full power after just a few seconds and is ready for long-term usage. With an operating level of 24 $V_{DC}$ and continuous power of 500 Watt there are several more applications which can be powered. Parallel connection of the modules is possible. For education, research and development the measurement data and operating parameters can be monitored via digital port.

Within a joint research project the Technical University of Chemnitz [7] integrates the described fuel cell system module into an autonomous transport system. Therefore a power electronics / super capacitor setup is attached and supervising energy management algorithms are being applied. The modular fuel cell system concept here allows to operate the system under the full control of the energy management but without any direct data connection to the fuel cell system controller, which acts individually reacting on the current demand of the attached power electronics.

## 5 $H_2$ - Application: Uninterrupted Power Supply (UPS)

Uninterrupted power supply systems (UPS) for telecommunication are already under discussion both for centralized applications as well as for decentralized applications. Remote repeater stations which have an electrical consumption of less than 750 $W_{el}$ are more and more equipped with UPS systems based on either batteries or super capacitors. With decreasing reliability of electric mains the length of power outages is increasing. The more telecommunication is a necessary part of everyday life the more raises the demand for long term power backup of the telecommunication networks.

Using hydrogen powered fuel cells as long term energy source in addition to short term storage devices such as super capacitors is an environmentally and economically interesting option for decentralized backup systems. A solution for an outdoor cabinet integrated fuel cell powered UPS has been developed. The system architecture is optimized for traffic components but is already including the classic power supply technologies for telecommunication applications. The back-up power system contains a hydrogen powered fuel cell system, a UPS module and a supervising controller unit.

The 650 $W_{el}$ stack is integrated into a highly developed system architecture which includes all necessary peripheral components (eg. pumps, valves, fans) as well as control electronics and routines. The control algorithms are developed fulfilling the demands of stationary independent fuel cell systems including e.g temperature management during operation and stand by and vital testing in times of non operation of the system. All components are integrated into standard 19’’ racks, using internal heat management.

**Figure 7: System operation in Northern Sweden.**

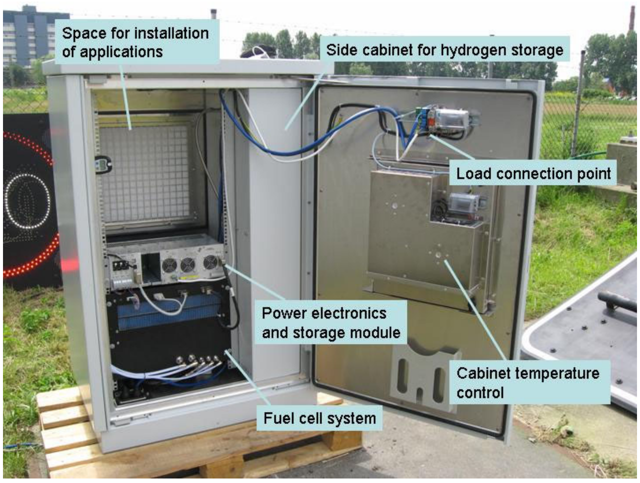



**Figure 8: UPS operation in the Netherlands.**

The UPS module is based on a DC/DC Converter and a capacitor block with double layer capacitors. A bidirectional DC/DC converter is connected to the internal 48V DC bus and is charging the capacitors when public mains are available. At mains failure the DC/DC converter is powering the 48 V DC bus by discharging the capacitors. Connected to the 48 V bus is the DC/AC converter powering the loads. The capacitor block is powering the start-up time of the fuel cell system and secures smooth system behaviour on any load changes and short time power peaks.

The described modular components (power electronics, capacitors, fuel cell system) are mounted into standard cabinets (see Figure 8) either for indoor or outdoor use. The double-walled outdoor cabinets include a tempering module for winter or summer use securing a rapid system start-up at any net outage. Using this approach typical outdoor temperature ranges from minus 40 °C to plus 45 °C can be served. The operation under freezing conditions was demonstrated during a one week field trial in Northern Sweden in January 2009 (see Figure 7) The cabinet also includes a separated storage cabin for standard 10 $l_N$ 200 bar hydrogen bottles.

Application for this system architecture is the uninterrupted power supply of traffic control components as well as decentralized telecommunication devices. To increase the backup time of the standard UPS modules (power electronics and supercapacitors) they are now supported by the described fuel cell module. Average loads of up to 500 $W_{el}$ can be securely powered by using this setup. On full load two standard bottles hydrogen (200 bar / 10 $l_N$) are able to supply energy for at least 8 hrs of operation which is more than regular mains failures least in the UCTE networks.

## 6 Conclusion

Applications for which fuel cells give the highest added value are situated in the field of auxiliary power units (APU) and other low power applications. In the range of 100 $W_{el}$ up to 500 $W_{el}$ (net power) the fuel cell research centre ZBT ("Zentrum für BrennstoffzellenTechnik gGmbH") recently has developed and demonstrated different hydrogen fuel cell based power supply layouts. These systems which include ZBT's air cooled APU-stack technology have been used for demonstration and application purposes for various applications in the field of decentralized electrical energy supply.

**Acknowledgement**

Thanks to "Verein für Energie und Umwelttechnik e.V." for sponsoring this project (286ZBG) with allocated funds from "Bundesministerium für Wirtschaft und Technologie (BMWi)" through „Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto-von-Guericke" e.V. (AiF)" and to the Partner Institutes at Technical University of Chemnitz.

**References**

[1] Kreuz, C.: PEM-Brennstoffzellen mit spritzgegossenen Bipolarplatten aus hochgefülltem Graphit-Compound, Dissertation, 2008, University of Duisburg-Essen

[2] Kreuz, C.: Massenproduktionstechniken zur Herstellung von Brennstoffzellen-Komponenten, Brennstoffzelle - Forschung - Demonstration - Anwendung - VDI-Berichte 2036 - ISBN 978-3-18-092036-8

[3] Beckhaus, P.: "Optimized fuel cell stacks for portable and mobile applications", Hydrogen & Fuel Cells 2007: International Conference and Trade Show - Vancouver, Canada, 29. April - 02. Mai 2007

[4] Beckhaus, P. et al: "PEM fuel cell stacks and efficient system topologies for hydrogen based low power applications", Fuel Cell Science & Technology 2006 - Scientific Advance in Fuel Cell Systems, 2006, Turin

[5] Beckhaus, P. et al: "Uninterrupted power supply - supported by fuel cells", Telescon 2009, Vienna

[6] Priwitzer, H. et. al: "Moded-based Control Design Techniques for small Systems using low-power Microcontrollers" proceedings of Embedded World 2009 - Exhibition&Conference, March 3-5, 2009, Nürnberg

[7] Bocklisch, T. et. al.: „Control-oriented, optimizing energy management concept for fuel cell hybrid systems" proceedings of PCIM (Power Conversion Intelligent Motion) 2009

# Recent Development of Portable DMFC Influenced by Simplo-ITRI Cooperation

**Welkin Ling, Li-duan Tsai, Chiou-Chu Lai,** Industrial Technology Research Institute, Taiwan
**Mei-Hui Wang,** Simplo Technology, Ltd.

## 1 Who Are Simplo and ITRI?

The main business of Simplo Technology Ltd. is providing ODM battery packs for notebook computer manufacturers. Its global market share in this segment is 22.3% in 2008 for 29 million pieces battery packs. It has about 5000 employees worldwide and generated 976 million USD revenue in 2008.


**Figure 1**

ITRI (the Industrial Technology Research Institute) is a non-profit research institute located in Taiwan under the supervision of the Republic of China Ministry of Economic Affairs, with over 6000 employees and an operating budget of about US$ 510 million (half from the MOEA and half from private sources). ITRI has been working on FC R&D since 2001 mainly focused on PEMFC and DMFC, currently with about 70 people and 4M Euro combined.

**Figure 2**

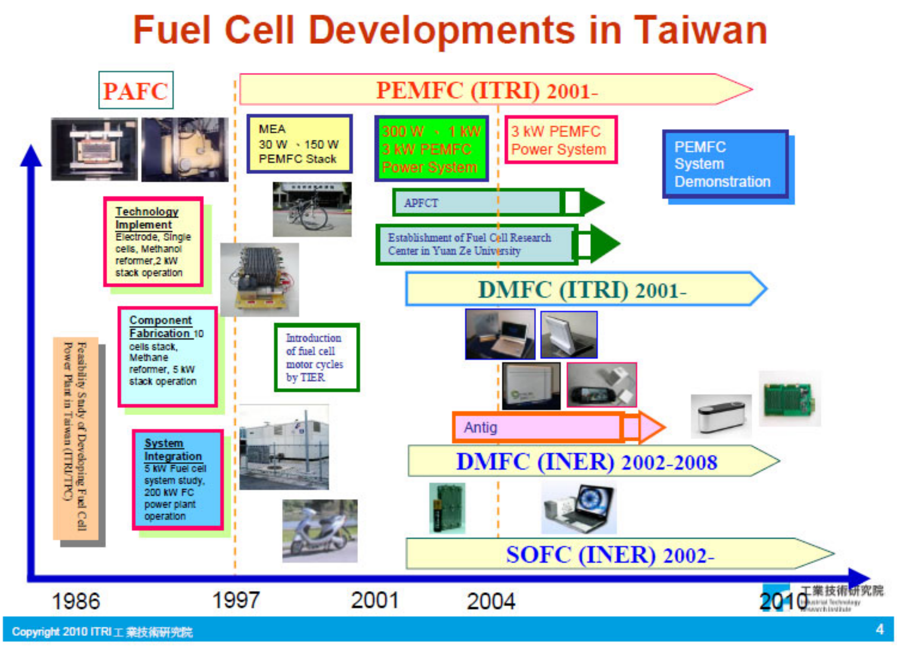



**Figure 3**

In this poster, the emphasis will be on the “DMFC MEA (Membrane Electrode Assembly)” and “DMFC/Li-ion Battery hybrid power supply controller”.

## 2 DMFC/Li-ion Battery Hybrid Power Supply Controller

With the consideration as an add-on FC power supply for Li-ion battery powered portable electronics, a patented “Dual Tracking hybrid controller” is developed. The core control strategy is to measure the secondary battery voltage to determine Fuel cell operation mode.

When battery voltage is below the setting value, the FC operation will be controlled at a constant voltage. In this case, each FC cell will run at a pre-determined voltage. This voltage value is based on the optimum condition that was determined for a specific fuel cell system. The converter output voltage will follow the voltage of the battery. It means FC will run at constant power (voltage) stage and battery will discharge when extra power is required and recharge when FC output power is higher than load.

When battery voltage is higher than the setting value, the controller will change its control mode. In this mode converter output voltage will be set at battery charging voltage. The FC will run at a high voltage to get higher conversion efficiency or higher fuel efficiency depending on the application requirement. In this case the fuel supply needs to be controlled to avoid the waste of fuel.

Compared to the Dual Tracking hybrid controller, fuel cell equipped with traditional fuel cell controller has to frequently change their operating voltage according to the load. The FC system's durability and fuel efficiency may be adversely affected under this condition.

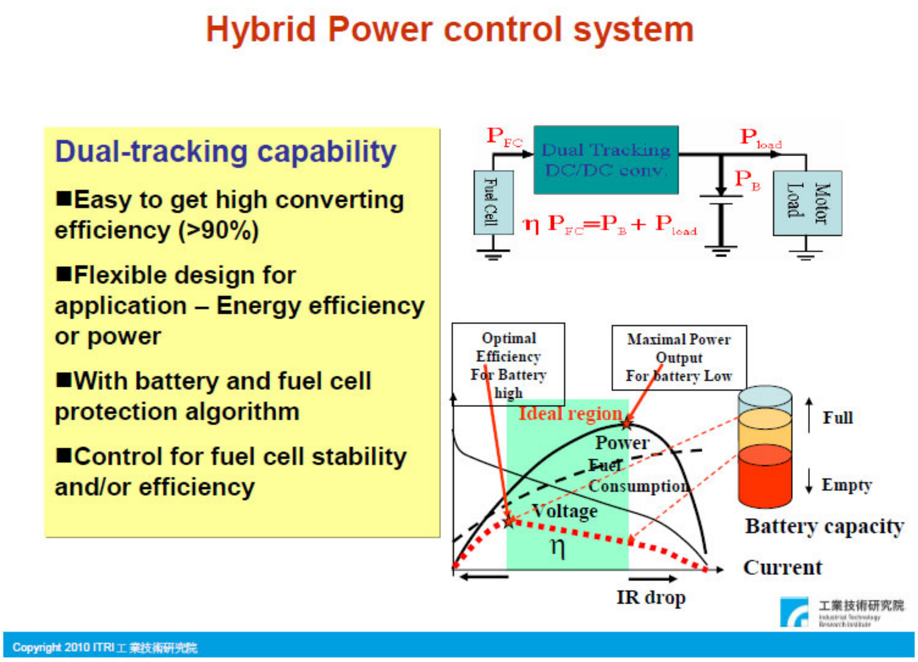



**Figure 4**

## 3 DMFC MEA development in ITRI

When the DMFC MEA is used in a passive/semi-passive system which lacks sophisticate fuel/air supply devices, the material design and manufacturing process development of MEA become very important. ITRI's current DMFC MEA, when tested in performance/characteristics verification setup, is shown to have both good power density (120mW/cm2) and durability (10% decay after 1500 hrs discharging).

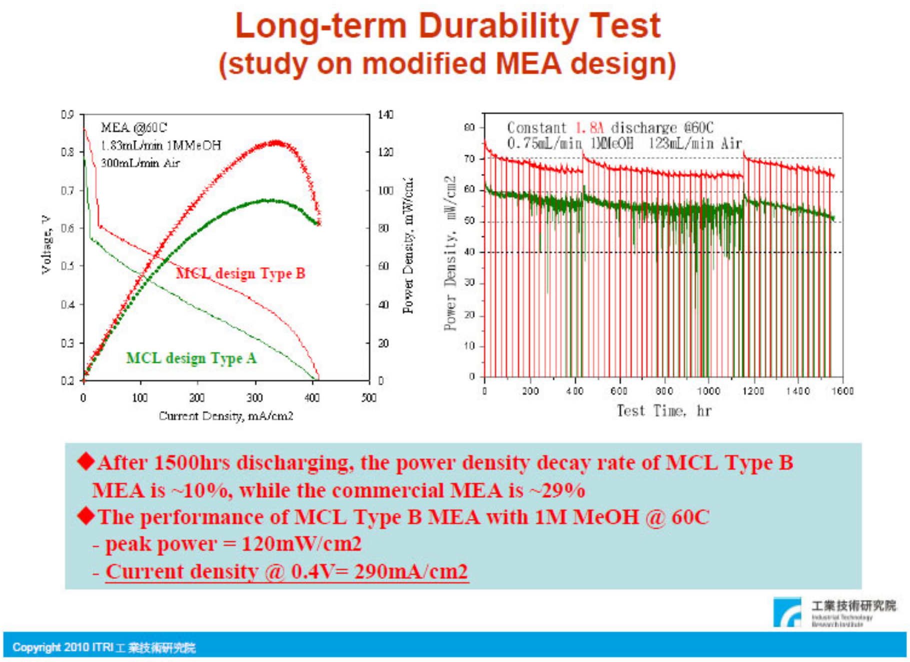



**Figure 5**

The above progress mainly comes from better Pt/C dispersion technique and improved catalyst coating process to the MEA.

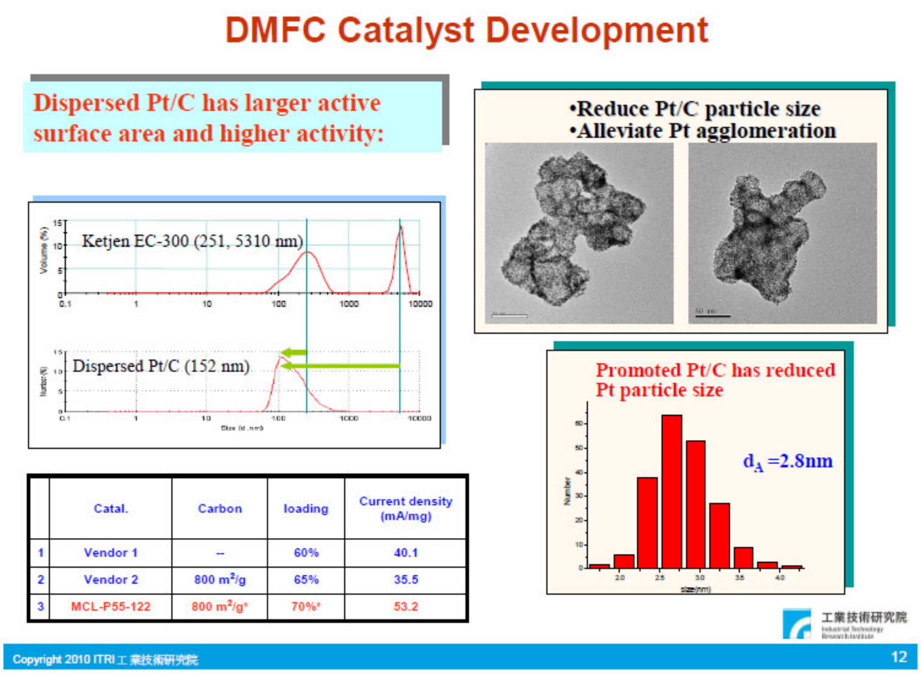



**Figure 6**

## 4 Summary

By working toward the design requirements from notebook battery pack market leader, e.g. Simplo Technology Ltd., both active and passive portable electronics DMFC prototypes have been developed in recent years. Those DMFC prototypes are also good proving ground to show the effectiveness of tailor-made MEAs and DMFC/Li-ion battery hybrid power supply controller.

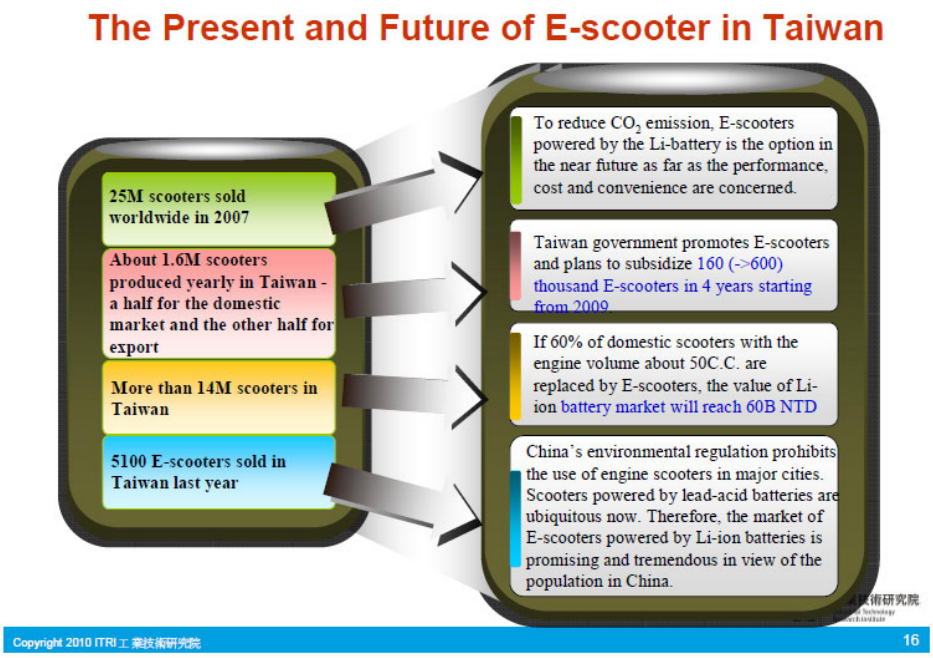



**Figure 7**

In ITRI we consider multi-lateral cooperation, such as demonstration or R&D projects under EU-FP7, is a good way to facilitate the commercialization of fuel cell technologies. Simplo and ITRI, a long time partners in portable DMFC R&D, welcome the opportunity to establish a cross-linking project between existing demonstration projects in Germany (EU) and Taiwan (e.g., the e-scooter project).

# Hybridization and Control of Direct Methanol Fuel Cell Systems for Material Handling Applications

**J. Wilhelm, L. Blum, H. Janßen, J. Mergel, D. Stolten,** Forschungszentrum Jülich GmbH, Germany

## 1 Introduction

In the last few years several systems for light traction applications with a DMFC have been set up at Forschungszentrum Jülich GmbH (IEF-3) [1] [2]. A current project with industrial partners deals with a horizontal order picker as shown in Figure 1. Aim of this project is to replace the original traction battery by a DMFC system, which has several advantages:

- longer operating times
- no recharging of the batteries
- no need for spare batteries
- easy handling and unproblematic refuelling

A horizontal order picker is a small fork-lift truck, which is used in large warehouses for material handling applications. The typical operation of this vehicle can be described by a characteristic driving cycle, as shown in Figure 1. Table 1 gives an overview of the different power values of the characteristic driving cycle. Although the maximum peak power is exceeding 6 kW, the average power of the driving cycle is only 800 W. The maximum driving power, where the vehicle is running at its maximum speed, is 2.4 kW.

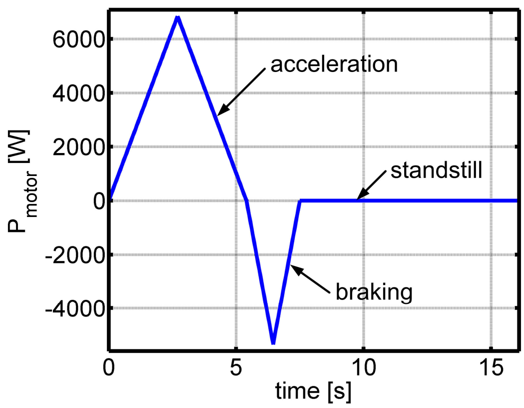



**Figure 1: Characteristic driving cycle (left) of a horizontal order picker (right).**

**Table 1: Accelerating, braking and driving power.**

| | |
|---|---|
| **Accelerating power** | 6800 W |
| **Braking power** | -5300 W |
| **Average power of driving cycle** | 800 W |
| **Maximum driving power** | 2400 W |

## 2 Hybridization Concept

The electric subsystem connecting the DMFC stack to the driving motor is set up as a hybrid system. There are several reasons for hybridizing a fuel cell:

- limited dynamic behaviour of the fuel cell [3]
- need for energy recovery during braking [4]
- dimensions of the fuel cell can be reduced [5]
- start-up of the fuel cell system [6]

Several configurations for the hybridization are possible. Basically series hybrid systems can be divided into two groups: active and passive hybrids [7]. Passive hybrids represent a direct coupling between the fuel cell (FC) and the energy storage (ES). Whereas in active hybrids they are coupled via converters. For a hybrid with one fuel cell and one energy storage device there are according to [8] four basic concepts (see Figure 2).

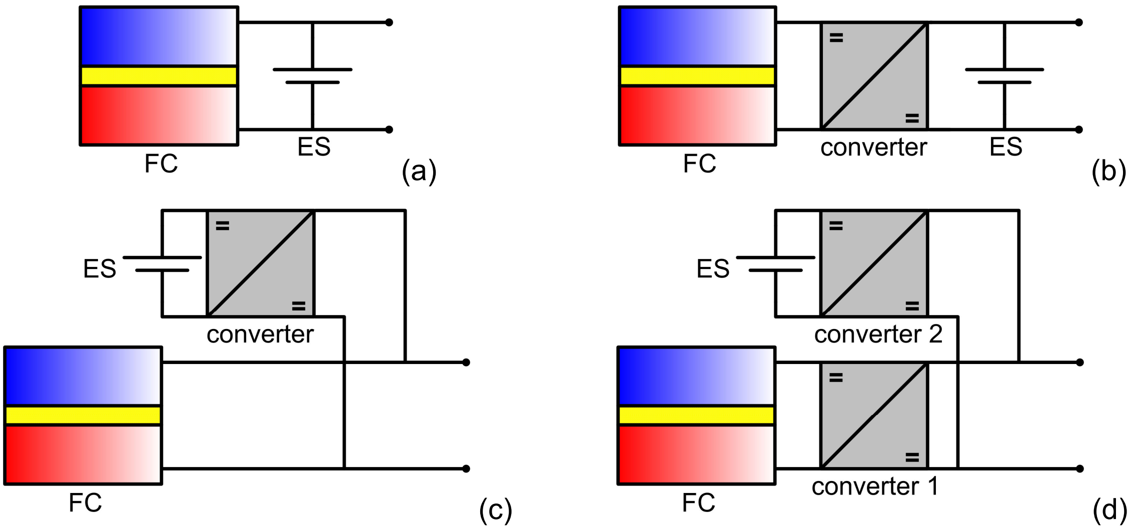



**Figure 2: Basic concepts.**

For the decision which concept is the best for the considered application the following three criteria were analyzed with simulations and experiments:

- system efficiency
- needed fuel cell power
- dynamic behaviour of the fuel cell

Simulations show that basic concept (a) has the best system efficiency (29.2 %) and needs the least fuel cell power (1.2 kW) [8]. The second best concept is basic concept (b) with 26.3 % system efficiency and 1.3 kW needed fuel cell power [8]. As they represent the two groups active and passive hybrid the dynamic behaviour of the fuel cell was analyzed. Simulations and experiments show that the amplitudes within the dynamic behaviour of the fuel cell are smaller for basic concept (b) as the converter decouples the fuel cell from the highly fluctuating driving profile [8]. So for this application basic concept (b) was chosen, resulting in the hybrid system setup in Figure 3.

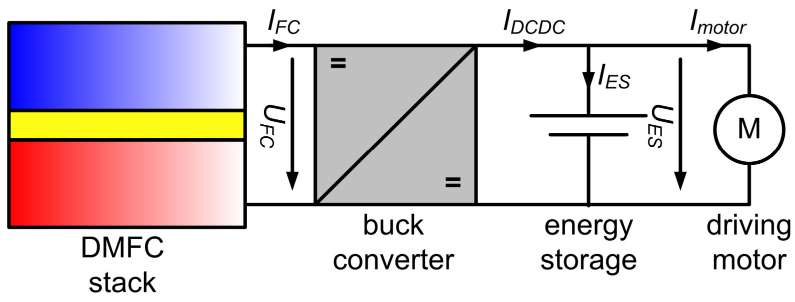



**Figure 3: DMFC hybrid system.**

# 3 Dimensioning of DMFC Stack and Energy Storage

## 3.1 Dimensioning of the DMFC stack

The main goal of the control strategy (see chapter 4) is to maintain the state of charge (SOC) of the energy storage on a constant level. So the useable electric power from the DMFC stack should be equal to the average driving power of the motor plus system losses from the buck converter (DCDC) and the energy storage (ES). Furthermore the power consumption of the peripheral components must be covered. With the energy flow diagram in Figure 4 the needed DMFC stack power is 1.3 kW as described in chapter 2.

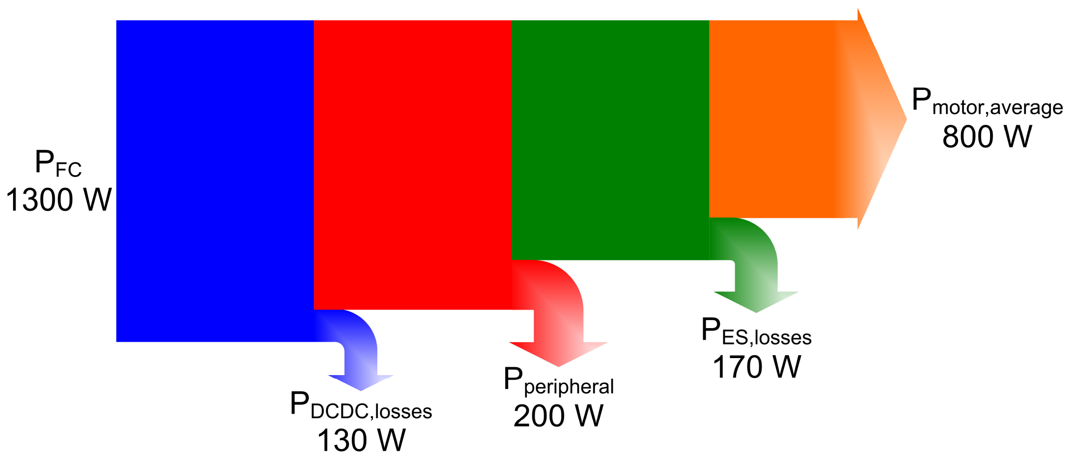



**Figure 4: Energy flow diagram.**

## 3.2 Dimensioning of the energy storage

Dimensioning parameters for the energy storage are the maximum energy content and the maximum power (charge and discharge), which are influenced by the operating states of the application (see Table 2):

- State 1: heating-up of the DMFC stack
- State 2: normal operation with average driving power (see Table 1)
- State 3: abnormal operation with maximum driving power (see Table 1)

**Table 2: Operating states and their influence on the dimensioning.**

| State | $P_{FC}$ | Driving power from … | Influence on … | |
|---|---|---|---|---|
| | | | energy content | charge/discharge power |
| 1 | = 0 | ES | Yes | Yes |
| 2 | ≠ 0 | FC + ES | No | Yes |
| 3 | ≠ 0 | FC + ES | Yes | No |

During heating-up the DMFC stack delivers no electric power, so the driving power only comes from the energy storage (ES). Whereas during normal and abnormal operation the DMFC stack delivers an average power according to chapter 3.1. Here the driving is done with the fuel cell (FC) and the energy storage (ES). During normal operation the energy storage will stay on a fixed state of charge (see chapter 4). So this has no influence on the needed energy content. When the vehicle is only driven by the energy storage (State 1) the energy storage will be discharged, resulting in a needed energy content. If the driving power is higher than the average driving power (State 3) the energy storage will also be discharged. The main task of the energy storage is to be discharged during acceleration and to be charged during braking. So during heating-up and normal operation the maximum charge and discharge power can be taken from Table 1. As there is no acceleration and braking during abnormal operation this has no influence on the maximum power.

As the space for the complete DMFC system is limited by the original battery box in this case for the energy storage only 20 l are left. The minimum values for energy density and power density of the energy storage can thus be calculated according to Table 3. For the decision which kind of energy storage will be suitable a Ragone chart is used [8]. The Ragone chart with the performance limits according to Table 3 can be seen in Figure 5. It becomes clear that the energy density of super capacitors is too small. So a battery, in this case a lithium-ion-battery, was chosen [8].

**Table 3: Performance limits for energy storage.**

| | |
|---|---|
| **Energy density** | 65 Wh/l |
| **Power density** | 350 W/l |

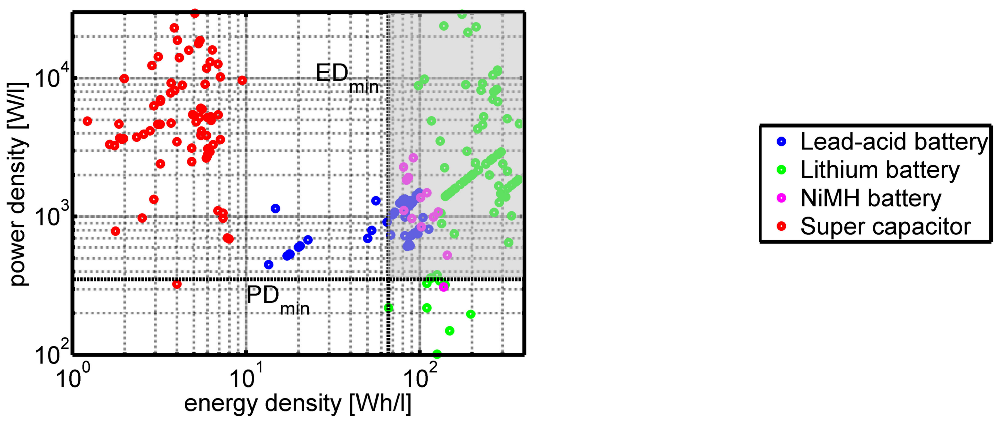



**Figure 5: Ragone chart with performance limits.**

## 4 Control Strategy

To control the power flow between the DMFC stack and the energy storage (here: battery) in such an active series hybrid a control strategy is needed. Figure 6 illustrates the main structure of the control system, consisting of three controllers. The different currents and voltages can be taken from Figure 3. The main goal of the control strategy is to maintain the state of charge of the energy storage on a constant level. A possible control value, which is shown in Figure 6, is the actual energy storage voltage $U_{ES,a}$. With this control variable “controller 1” calculates the desired DMFC stack voltage $U_{FC,d}$, which is limited to a minimum value depending on the actual fuel cell temperature $T_{FC,a}$. This limitation has the aim of avoiding aging of the fuel cell caused by catalyst corrosion [9]. The deviation from the actual fuel cell voltage $U_{FC,a}$ is the input for “controller 2”. The output of this controller is the desired current $I_{DCDC,d}$ at the output of the buck converter. The described limitation block has the aim of avoiding aging of the fuel cell. The aim of the “map control” is also related to aging and deals with the identification of an aging process. A characteristic map is implemented, which describes the behaviour of an unaged fuel cell. From this a theoretical fuel cell current is calculated, which is compared with the actual fuel cell current $I_{FC,a}$. The result of this comparison is a correction factor, which is used to adjust the methanol mass flow $\dot{m}_{MeOH}$ and the air volume flow $\dot{V}_{air}$ compared to their standard values for the unaged fuel cell [10].

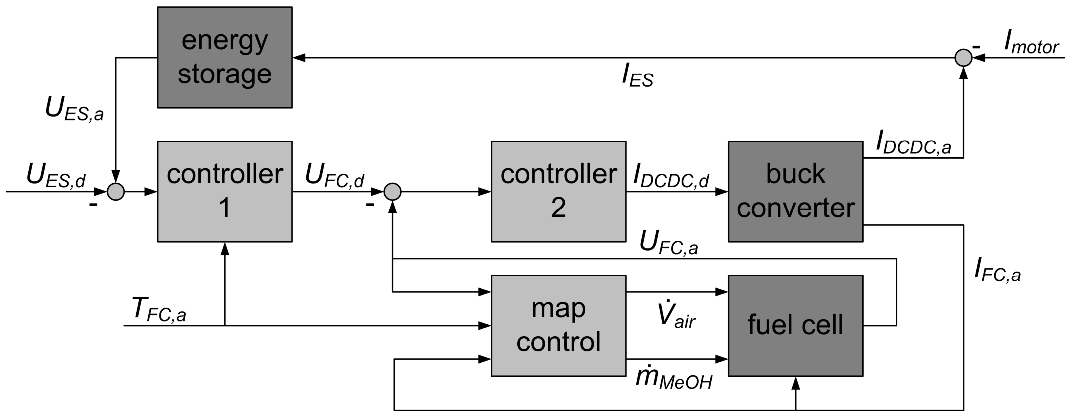



**Figure 6: Structure of the control system.**

## 5 Conclusions

There are several advantages in replacing the lead-acid battery, such as faster refuelling and extended operating time. Because of the highly fluctuating load profile, the DMFC stack has to be hybridized. In this case an active series hybrid is the best solution. The dimensioning of the DMFC stack and the energy storage has to be done in the run-up according to the requirements of the load profile. Requirements for the energy storage are a high energy density and a high power density. Therefore only batteries come into consideration. For the hybrid system it is important to have a control strategy. The control strategy presented has two aims regarding aging of the fuel cell: avoiding of aging and identification of aging.

**References**

[1] H. Janßen, L. Blum, N. Kimiaie, A. Maintz, J. Mergel, M. Müller, D. Stolten: "Performance Characterization of a 4-Wheel DMFC Scooter" Proceedings "3rd European PEFC Forum", 04 - 08.07.2005, Lucerne, Switzerland

[2] M. Nölke: "Entwicklung, Auslegung und Umsetzung eines DMFC-Systems der kW-Klasse" PhD Thesis, RWTH Aachen University, 2007

[3] O. Garcia: "DC/DC-Wandler für die Leistungsverteilung in einem Elektrofahrzeug mit Brennstoffzellen und Superkondensatoren" PhD Thesis, ETH Zurich University, 2002

[4] A. Di Napoli, F. Crescimbini, L. Solero, G. Pede, G. Lo Bianco, M. Pasquali: "Ultracapacitor and Battery Storage System Supporting Fuel-Cell Powered Vehicles" Proceedings "18th International Electric Vehicle Symposium (EVS 18)", 20 - 24.10.2001, Berlin, Germany

[5] K. Seong Jeong, B. Soo Oh: "Fuel economy and life-cycle cost analysis of a fuel cell hybrid vehicle" Journal of Power Sources, Vol. 105, 2002, pp. 58 - 65

[6] T. Markel, A. Pesaran: "Energy Storage System for Fuel Cell Hybrid Vehicles. Status Report" Proceedings "Joint VSATT and ESTT Meeting", 16.02.2006

[7] M. J. Blackwelder, R. A. Dougal: "Power coordination in a fuel cell-battery hybrid power source using commercial power controller circuits" Journal of Power Sources, Vol. 134, 2004, pp. 139 - 147

[8] J. Wilhelm: "Hybridisierung und Regelung eines mobilen Direktmethanol-Brennstoffzellen-Systems" 2010

[9] R. Steinberger-Wilckens, J. Mergel, A. Glüsen, K. Wippermann, I. C. Vinke, P. Batfalsky, M. J. Smith: "Performance degradation and failure mechanisms of fuel cell materials" Materials for fuel cells, October 2008, pp. 425 - 465

[10] M. Müller, A, Maintz, J. Wilhelm, H. Janssen, D. Stolten: "Brennstoffzellensystem und Verfahren zur Regelung eines Brennstoffzellensystems" Patent application DE 10 2007 014 617 A1, 25.09.2008

1. **Einsatz von multispektralen Satellitenbilddaten in der Wasserhaushalts- und Stoffstrommodellierung – dargestellt am Beispiel des Rureinzugsgebietes**
von C. Montzka (2008), XX, 238 Seiten
ISBN: 978-3-89336-508-1

2. **Ozone Production in the Atmosphere Simulation Chamber SAPHIR**
by C. A. Richter (2008), XIV, 147 pages
ISBN: 978-3-89336-513-5

3. **Entwicklung neuer Schutz- und Kontaktierungsschichten für Hochtemperatur-Brennstoffzellen**
von T. Kiefer (2008), 138 Seiten
ISBN: 978-3-89336-514-2

4. **Optimierung der Reflektivität keramischer Wärmedämmschichten aus Yttrium-teilstabilisiertem Zirkoniumdioxid für den Einsatz auf metallischen Komponenten in Gasturbinen**
von A. Stuke (2008), X, 201 Seiten
ISBN: 978-3-89336-515-9

5. **Lichtstreuende Oberflächen, Schichten und Schichtsysteme zur Verbesserung der Lichteinkopplung in Silizium-Dünnschichtsolarzellen**
von M. Berginski (2008), XV, 171 Seiten
ISBN: 978-3-89336-516-6

6. **Politikszenarien für den Klimaschutz IV – Szenarien bis 2030**
hrsg.von P. Markewitz, F. Chr. Matthes (2008), 376 Seiten
ISBN 978-3-89336-518-0

7. **Untersuchungen zum Verschmutzungsverhalten rheinischer Braunkohlen in Kohledampferzeugern**
von A. Schlüter (2008), 164 Seiten
ISBN 978-3-89336-524-1

8. **Inorganic Microporous Membranes for Gas Separation in Fossil Fuel Power Plants**
by G. van der Donk (2008), VI, 120 pages
ISBN: 978-3-89336-525-8

9. **Sinterung von Zirkoniumdioxid-Elektrolyten im Mehrlagenverbund der oxidkeramischen Brennstoffzelle (SOFC)**
von R. Mücke (2008), VI, 165 Seiten
ISBN: 978-3-89336-529-6

10. **Safety Considerations on Liquid Hydrogen**
by K. Verfondern (2008), VIII, 167 pages
ISBN: 978-3-89336-530-2

11. **Kerosinreformierung für Luftfahrtanwendungen**
von R. C. Samsun (2008), VII, 218 Seiten
ISBN: 978-3-89336-531-9

12. **Der 4. Deutsche Wasserstoff Congress 2008 – Tagungsband**
hrsg. von D. Stolten, B. Emonts, Th. Grube (2008), 269 Seiten
ISBN: 978-3-89336-533-3

13. **Organic matter in Late Devonian sediments as an indicator for environmental changes**
by M. Kloppisch (2008), XII, 188 pages
ISBN: 978-3-89336-534-0

14. **Entschwefelung von Mitteldestillaten für die Anwendung in mobilen Brennstoffzellen-Systemen**
von J. Latz (2008), XII, 215 Seiten
ISBN: 978-3-89336-535-7

15. **RED-IMPACT**
**Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal**
**SYNTHESIS REPORT**
ed. by W. von Lensa, R. Nabbi, M. Rossbach (2008), 178 pages
ISBN 978-3-89336-538-8

16. **Ferritic Steel Interconnectors and their Interactions with Ni Base Anodes in Solid Oxide Fuel Cells (SOFC)**
by J. H. Froitzheim (2008), 169 pages
ISBN: 978-3-89336-540-1

17. **Integrated Modelling of Nutrients in Selected River Basins of Turkey**
Results of a bilateral German-Turkish Research Project
project coord. M. Karpuzcu, F. Wendland (2008), XVI, 183 pages
ISBN: 978-3-89336-541-8

18. **Isotopengeochemische Studien zur klimatischen Ausprägung der Jüngeren Dryas in terrestrischen Archiven Eurasiens**
von J. Parplies (2008), XI, 155 Seiten, Anh.
ISBN: 978-3-89336-542-5

19. **Untersuchungen zur Klimavariabilität auf dem Tibetischen Plateau - Ein Beitrag auf der Basis stabiler Kohlenstoff- und Sauerstoffisotope in Jahrringen von Bäumen waldgrenznaher Standorte**
von J. Griessinger (2008), XIII, 172 Seiten
ISBN: 978-3-89336-544-9

20. **Neutron-Irradiation + Helium Hardening & Embrittlement Modeling of 9%Cr-Steels in an Engineering Perspective (HELENA)**
by R. Chaouadi (2008), VIII, 139 pages
ISBN: 978-3-89336-545-6

21. **in Bearbeitung**

22. **Verbundvorhaben APAWAGS (AOEV und Wassergenerierung) – Teilprojekt: Brennstoffreformierung – Schlussbericht**
von R. Peters, R. C. Samsun, J. Pasel, Z. Porš, D. Stolten (2008), VI, 106 Seiten
ISBN: 978-3-89336-547-0

23. **FREEVAL**
Evaluation of a Fire Radiative Power Product derived from Meteosat 8/9 and Identification of Operational User Needs
Final Report
project coord. M. Schultz, M. Wooster (2008), 139 pages
ISBN: 978-3-89336-549-4

24. **Untersuchungen zum Alkaliverhalten unter Oxycoal-Bedingungen**
von C. Weber (2008), VII, 143, XII Seiten
ISBN: 978-3-89336-551-7

25. **Grundlegende Untersuchungen zur Freisetzung von Spurstoffen, Heißgaschemie, Korrosionsbeständigkeit keramischer Werkstoffe und Alkalirückhaltung in der Druckkohlenstaubfeuerung**
von M. Müller (2008), 207 Seiten
ISBN: 978-3-89336-552-4

26. **Analytik von ozoninduzierten phenolischen Sekundärmetaboliten in *Nicotiana tabacum* L. cv Bel W3 mittels LC-MS**
von I. Koch (2008), III, V, 153 Seiten
ISBN 978-3-89336-553-1

27. **IEF-3 Report 2009. Grundlagenforschung für die Anwendung**
(2009), ca. 230 Seiten
ISBN: 978-3-89336-554-8

28. **Influence of Composition and Processing in the Oxidation Behavior of MCrAlY-Coatings for TBC Applications**
by J. Toscano (2009), 168 pages
ISBN: 978-3-89336-556-2

29. **Modellgestützte Analyse signifikanter Phosphorbelastungen in hessischen Oberflächengewässern aus diffusen und punktuellen Quellen**
von B. Tetzlaff (2009), 149 Seiten
ISBN: 978-3-89336-557-9

30. **Nickelreaktivlot / Oxidkeramik – Fügungen als elektrisch isolierende Dichtungskonzepte für Hochtemperatur-Brennstoffzellen-Stacks**
von S. Zügner (2009), 136 Seiten
ISBN: 978-3-89336-558-6

31. **Langzeitbeobachtung der Dosisbelastung der Bevölkerung in radioaktiv kontaminierten Gebieten Weißrusslands – Korma-Studie**
von H. Dederichs, J. Pillath, B. Heuel-Fabianek, P. Hill, R. Lennartz (2009), Getr. Pag.
ISBN: 978-3-89336-532-3

32. **Herstellung von Hochtemperatur-Brennstoffzellen über physikalische Gasphasenabscheidung**
von N. Jordán Escalona (2009), 148 Seiten
ISBN: 978-3-89336-532-3

33. **Real-time Digital Control of Plasma Position and Shape on the TEXTOR Tokamak**
by M. Mitri (2009), IV, 128 pages
ISBN: 978-3-89336-567-8

34. **Freisetzung und Einbindung von Alkalimetallverbindungen in kohle-befeuerten Kombikraftwerken**
von M. Müller (2009), 155 Seiten
ISBN: 978-3-89336-568-5

35. **Kosten von Brennstoffzellensystemen auf Massenbasis in Abhängigkeit von der Absatzmenge**
von J. Werhahn (2009), 242 Seiten
ISBN: 978-3-89336-569-2

36. **Einfluss von Reoxidationszyklen auf die Betriebsfestigkeit von anodengestützten Festoxid-Brennstoffzellen**
von M. Ettler (2009), 138 Seiten
ISBN: 978-3-89336-570-8

37. **Großflächige Plasmaabscheidung von mikrokristallinem Silizium für mikromorphe Dünnschichtsolarmodule**
von T. Kilper (2009), XVII, 154 Seiten
ISBN: 978-3-89336-572-2

38. **Generalized detailed balance theory of solar cells**
by T. Kirchartz (2009), IV, 198 pages
ISBN: 978-3-89336-573-9

39. **The Influence of the Dynamic Ergodic Divertor on the Radial Electric Field at the Tokamak TEXTOR**
von J. W. Coenen (2009), xii, 122, XXVI pages
ISBN: 978-3-89336-574-6

40. **Sicherheitstechnik im Wandel Nuklearer Systeme**
von K. Nünighoff (2009), viii, 215 Seiten
ISBN: 978-3-89336-578-4

41. **Pulvermetallurgie hochporöser NiTi-Legierungen für Implanat- und Dämpfungsanwendungen**
von M. Köhl (2009), XVII, 199 Seiten
ISBN: 978-3-89336-580-7

42. **Einfluss der Bondcoatzusammensetzung und Herstellungsparameter auf die Lebensdauer von Wärmedämmschichten bei zyklischer Temperaturbelastung**
von M. Subanovic (2009), 188, VI Seiten
ISBN: 978-3-89336-582-1

43. **Oxygen Permeation and Thermo-Chemical Stability of Oxygen Permeation Membrane Materials for the Oxyfuel Process**
by A. J. Ellett (2009), 176 pages
ISBN: 978-3-89336-581-4

44. **Korrosion von polykristallinem Aluminiumoxid (PCA) durch Metalljodidschmelzen sowie deren Benetzungseigenschaften**
von S. C. Fischer (2009), 148 Seiten
ISBN: 978-3-89336-584-5

45. **IEF-3 Report 2009. Basic Research for Applications**
(2009), 217 Seiten
ISBN: 978-3-89336-585-2

46. **Verbundvorhaben ELBASYS (Elektrische Basissysteme in einem CFK-Rumpf) - Teilprojekt: Brennstoffzellenabgase zur Tankinertisierung - Schlussbericht**
von R. Peters, J. Latz, J. Pasel, R. C. Samsun, D. Stolten
(2009), xi, 202 Seiten
ISBN: 978-3-89336-587-6

47. **Aging of $^{14}$C-labeled Atrazine Residues in Soil: Location, Characterization and Biological Accessibility**
by N. D. Jablonowski (2009), IX, 104 pages
ISBN: 978-3-89336-588-3

48. **Entwicklung eines energetischen Sanierungsmodells für den europäischen Wohngebäudesektor unter dem Aspekt der Erstellung von Szenarien für Energie- und $CO_2$ - Einsparpotenziale bis 2030**
von P. Hansen (2009), XXII, 281 Seiten
ISBN: 978-3-89336-590-6

49. **Reduktion der Chromfreisetzung aus metallischen Interkonnektoren für Hochtemperaturbrennstofzellen durch Schutzschichtsysteme**
von R. Trebbels (2009), iii, 135 Seiten
ISBN: 978-3-89336-591-3

50. **Bruchmechanische Untersuchung von Metall / Keramik-Verbundsystemen für die Anwendung in der Hochtemperaturbrennstoffzelle**
von B. Kuhn (2009), 118 Seiten
ISBN: 978-3-89336-592-0

51. **Wasserstoff-Emissionen und ihre Auswirkungen auf den arktischen Ozonverlust**
**Risikoanalyse einer globalen Wasserstoffwirtschaft**
von T. Feck (2009), 180 Seiten
ISBN: 978-3-89336-593-7

52. **Development of a new Online Method for Compound Specific Measurements of Organic Aerosols**
by T. Hohaus (2009), 156 pages
ISBN: 978-3-89336-596-8

53. **Entwicklung einer FPGA basierten Ansteuerungselektronik für Justageeinheiten im Michelson Interferometer**
von H. Nöldgen (2009), 121 Seiten
ISBN: 978-3-89336-599-9

54. **Observation – and model – based study of the extratropical UT/LS**
by A. Kunz (2010), xii, 120, xii pages
ISBN: 978-3-89336-603-3

55. **Herstellung polykristalliner Szintillatoren für die Positronen-Emissions-Tomographie (PET)**
von S. K. Karim (2010), VIII, 154 Seiten
ISBN: 978-3-89336-610-1

56. **Kombination eines Gebäudekondensators mit H2-Rekombinatorelementen in Leichwasserreaktoren**
von S. Kelm (2010), vii, 119 Seiten
ISBN: 978-3-89336-611-8

57. **Plant Leaf Motion Estimation Using A 5D Affine Optical Flow Model**
by T. Schuchert (2010), X, 143 pages
ISBN: 978-3-89336-613-2

58. **Tracer-tracer relations as a tool for research on polar ozone loss**
by R. Müller (2010), 116 pages
ISBN: 978-3-89336-614-9

59. **Sorption of polycyclic aromatic hydrocarbon (PAH) to Yangtze River sediments and their components**
by J. Zhang (2010), X, 109 pages
ISBN: 978-3-89336-616-3

60. **Weltweite Innovationen bei der Entwicklung von CCS-Technologien und Möglichkeiten der Nutzung und des Recyclings von $CO_2$**
Studie im Auftrag des BMWi
von W. Kuckshinrichs et al. (2010), X, 139 Seiten
ISBN: 978-3-89336-617-0

61. **Herstellung und Charakterisierung von sauerstoffionenleitenden Dünnschichtmembranstrukturen**
von M. Betz (2010), XII, 112 Seiten
ISBN: 978-3-89336-618-7

62. **Politikszenarien für den Klimaschutz V – auf dem Weg zum Strukturwandel, Treibhausgas-Emissionsszenarien bis zum Jahr 2030**
hrsg. von P. Hansen, F. Chr. Matthes (2010), 276 Seiten
ISBN: 978-3-89336-619-4

63. **Charakterisierung Biogener Sekundärer Organischer Aerosole mit Statistischen Methoden**
von C. Spindler (2010), iv, 163 Seiten
ISBN: 978-3-89336-622-4

64. **Stabile Algorithmen für die Magnetotomographie an Brennstoffzellen**
von M. Wannert (2010), ix, 119 Seiten
ISBN: 978-3-89336-623-1

65. **Sauerstofftransport und Degradationsverhalten von Hochtemperaturmembranen für CO2-freie Kraftwerke**
von D. Schlehuber (2010), VII, 139 Seiten
ISBN: 978-3-89336-630-9

66. **Entwicklung und Herstellung von foliengegossenen, anodengestützten Festoxidbrennstoffzellen**
von W. Schafbauer (2010), VI, 164 Seiten
ISBN: 978-3-89336-631-6

67. **Disposal strategy of proton irradiated mercury from high power spallation sources**
by S. Chiriki (2010), xiv, 124 pages
ISBN: 978-3-89336-632-3

68. **Oxides with polyatomic anions considered as new electrolyte materials for solid oxide fuel cells (SOFCs)**
by O. H. Bin Hassan (2010), vii, 121 pages
ISBN: 978-3-89336-633-0

69. **Von der Komponente zum Stack: Entwicklung und Auslegung von HT-PEFC-Stacks der 5 kW-Klasse**
von A. Bendzulla (2010), IX, 203 Seiten
ISBN: 978-3-89336-634-7

70. **Satellitengestützte Schwerewellenmessungen in der Atmosphäre und Perspektiven einer zukünftigen ESA Mission (PREMIER)**
von S. Höfer (2010), 81 Seiten
ISBN: 978-3-89336-637-8

71. **Untersuchungen der Verhältnisse stabiler Kohlenstoffisotope in atmosphärisch relevanten VOC in Simulations- und Feldexperimenten**
von H. Spahn (2010), IV, 210 Seiten
ISBN: 978-3-89336-638-5

72. **Entwicklung und Charakterisierung eines metallischen Substrats für nanostrukturierte keramische Gastrennmembranen**
von K. Brands (2010), vii, 137 Seiten
ISBN: 978-3-89336-640-8

73. **Hybridisierung und Regelung eines mobilen Direktmethanol-Brennstoff-zellen-Systems**
von J. Chr. Wilhelm (2010), 220 Seiten
ISBN: 978-3-89336-642-2

74. **Charakterisierung perowskitischer Hochtemperaturmembranen zur Sauerstoffbereitstellung für fossil gefeuerte Kraftwerksprozesse**
von S.A. Möbius (2010) III, 208 Seiten
ISBN: 978-3-89336-643-9

75. **Characterization of natural porous media by NMR and MRI techniques: High and low magnetic field studies for estimation of hydraulic properties**
by L.-R. Stingaciu (2010), 96 pages
ISBN: 978-3-89336-645-3

76. **Hydrological Characterization of a Forest Soil Using Electrical Resistivity Tomography**
by Chr. Oberdörster (2010), XXI, 151 pages
ISBN: 978-3-89336-647-7

77. **Ableitung von atomarem Sauerstoff und Wasserstoff aus Satellitendaten und deren Abhängigkeit vom solaren Zyklus**
von C. Lehmann (2010), 127 Seiten
ISBN: 978-3-89336-649-1

78. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Speeches and Plenary Talks**
ed. by D. Stolten, B. Emonts (2010)
ISBN: 978-3-89336-658-3

78-1. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Parallel Sessions Book 1:**
**Fuel Cell Basics / Fuel Infrastructures**
ed. by D. Stolten, T. Grube (2010), ca. 460 pages
ISBN: 978-3-89336-651-4

78-2. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Parallel Sessions Book 2:**
**Hydrogen Production Technologies – Part 1**
ed. by D. Stolten, T. Grube (2010), ca. 400 pages
ISBN: 978-3-89336-652-1

78-3. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Parallel Sessions Book 3:**
**Hydrogen Production Technologies – Part 2**
ed. by D. Stolten, T. Grube (2010), ca. 640 pages
ISBN: 978-3-89336-653-8

78-4. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Parallel Sessions Book 4:**
**Storage Systems / Policy Perspectives, Initiatives and Cooperations**
ed. by D. Stolten, T. Grube (2010), ca. 500 pages
ISBN: 978-3-89336-654-5

78-5. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Parallel Sessions Book 5:**
**Stategic Analysis / Safety Issues / Existing and Emerging Markets**
ed. by D. Stolten, T. Grube (2010), ca. 530 pages
ISBN: 978-3-89336-655-2

78-6. **$18^{th}$ World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
**Parallel Sessions Book 6:**
**Stationary Applications / Transportation Applications**
ed. by D. Stolten, T. Grube (2010), ca. 330 pages
ISBN: 978-3-89336-656-9

78 Set (7 Bände)

**18th World Hydrogen Energy Conference 2010 – WHEC2010 Proceedings**
eb. by D. Stolten, T. Grube, B. Emonts (2010)
ISBN: 978-3-89336-657-6

**Energy & Environment**
**Volume 78-5** Book 5

Vol. 78 ISBN 978-3-89336-658-3
Vol. 78-1 Book 1: ISBN 978-3-89336-651-4
Vol. 78-2 Book 2: ISBN 978-3-89336-652-1
Vol. 78-3 Book 3: ISBN 978-3-89336-653-8
Vol. 78-4 Book 4: ISBN 978-3-89336-654-5
**Vol. 78-5 Book 5: ISBN 978-3-89336-655-2**
Vol. 78-6 Book 6: ISBN 978-3-89336-656-9
Vol. 78 Set (complete book series): ISBN 978-3-89336-657-6

JÜLICH
FORSCHUNGSZENTRUM