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This document appeared in

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 1: Fuel Cell Basics / Fuel Infrastructures
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-1
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-651-4

icefuel® – An Infrastructure System for Cryogenic Hydrogen Storage, Distribution and Decentral Use

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1 Background

The rapidly growing worldwide energy needs and the diversification of the energy mix with an increasing share of renewable energies are challenging the existing energy infrastructures. At present, central grids dominate worldwide energy supply and distribution. More flexible solutions are required, especially those that integrate renewable energies more efficiently. In the case that larger energy quantities have to be stored, hydrogen has, in spite of losses during production and reconversion to electric power, a high potential as universal and clean secondary energy source [1-3]. Numerous demonstration projects worldwide already address this kind of chemical energy storage [e.g. 4, 5]. In most cases hydrogen is stored in the gaseous state under pressure at ambient temperature and reconverted to electricity close to the point of hydrogen generation. The transition to liquid hydrogen (LH2) promises - despite the additional liquefaction effort - efficiency advantages for the storage, distribution and decentralized reconversion of the hydrogen into electricity, heat and cooling energy.

2 *icefuel*® Concept

icefuel® (integrated cable energy system for fuel and power) is a flexible system for energy storage, distribution and decentral reconversion. The concept is based on the production and liquefaction of hydrogen to buffer large quantities of excess electricity, preferentially from fluctuating renewable energies like wind and solar power, thus facilitating the equilibration of power generation and demand at high shares of renewable energies. A concept schematic is shown in Figure 1.

Thus, the *icefuel*® system should be quite easily installable in addition to existing infrastructures. To keep installations costs low, it would be favourable to apply the concept to areas with high utilization densities.

The cryogenic hydrogen (< -233 °C) is distributed through a grid of superinsulated pipes. Due to its high specific energy density and low viscosity pipes with relatively small pipe dimensions are adequate. For example, a pipe diameter of less than 20 mm is sufficient to convey an energy flux of 10 MW over a distance of 10 km (based on lower heating value - LHV - of the hydrogen). Such pipes can principally be coiled. Being equipped with an appropriate superinsulation, the pipes could be laid like conventional underground cables (see figure 2). Ideally, the insulation material and handling should be adapted to cable manufacturing processes to allow for integration of other functionalities like power and data cables or optionally for a liquid nitrogen (LN2) heat shield (see figure 3).

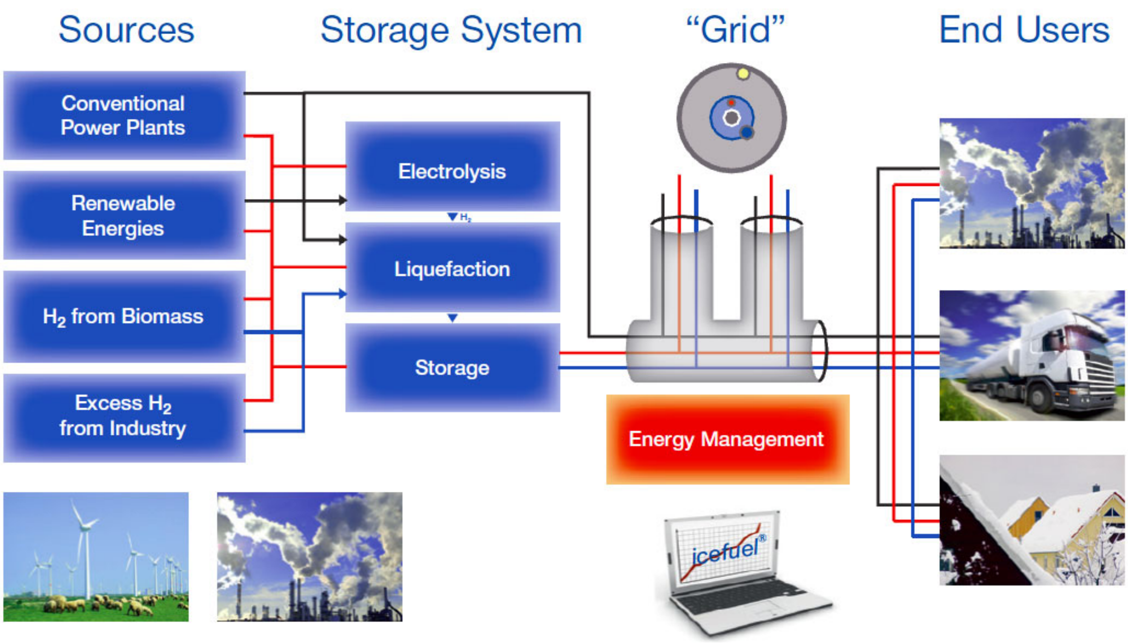

Figure 1: ***icefuel*® schematic.**

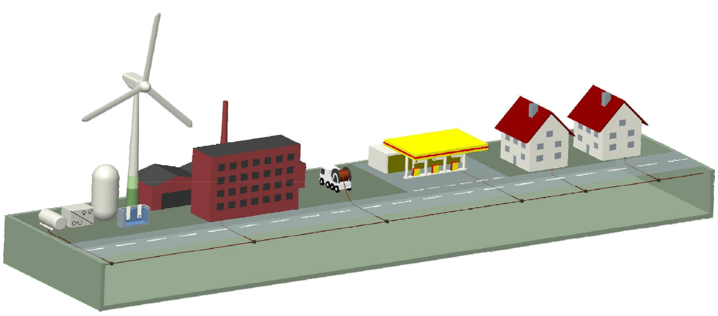

Figure 2: **Vision for *icefuel*® cable laying.**

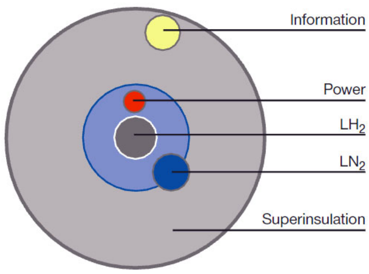

Figure 3: **Example schematic for an *icefuel*® cable.**

The electric efficiency of hydrogen based storage technologies (i.e. electricity via hydrogen back to electricity) is in general quite low (< 40 %). Conveying hydrogen to stationary end users enables combined heat and power production, thus, increasing the overall energetic efficiency significantly. Nevertheless, such an infrastructure concept should be combined with appropriate storage technologies covering short term charge and discharge needs. *icefuel*® is open for such a combination with other storage technologies.

3 Development project: Objectives, partners and achievements

In July 2006 a development project, funded by the Federal Ministry of Education and Research (Germany), was started. The objective was to gather fundamental and experimentally proven data about the technical feasibility of the *icefuel*® system. Since the cable is the key element in that infrastructure, the project focused on the cable design, manufacturing and testing as well as safety considerations regarding the transport of LH2 in cables. Due to the relatively small pipe dimensions, micro system technology concepts were included to provide solutions for heat exchangers, sensors and actuators.

The following partners were involved in the development project:

- DLR (German Aerospace Institute, Cologne)
- Evonik Degussa GmbH (Hanau)
- EWE AG (Oldenburg)
- IMM (Institute for Micro Technology, Mainz)
- KIT (Karlsruhe Institute of Technology, Karlsruhe); Institute for Micro Process Engineering (IMVT)
- KIT (Karlsruhe Institute of Technology, Karlsruhe); Institute for Nuclear and Energy Technologies (IKET)
- LEONI AG (Nuremberg)
- MMT (Engineering Office, Alzenau)
- TUEV SUED Industry Service GmbH (Munich)
- ZAE (Bavarian Centre for Applied Energy Research, Wuerzburg)

3.1 icefuel® cable

To allow for transport distances of up to 10 km the unavoidable heat fluxes into the pipe during operation with LH2 should be kept below 1 $W \cdot m^{-1}$. Compared to conventional district heating pipes this requires two orders of magnitude higher insulation performance. Thus, the major development challenge for the cable and its insulation material was to combine the excellent insulation properties with a continuous processability.

After a broad screening of materials, designs and processing technologies finally a concept was identified and successfully tested on various cable samples at lengths of tens of meters. The concept allows for continuous manufacture of mechanically flexible, endless-type pipes (see figure 4). Other functionalities have not yet been realized in the cable, but could be integrated quite easily.

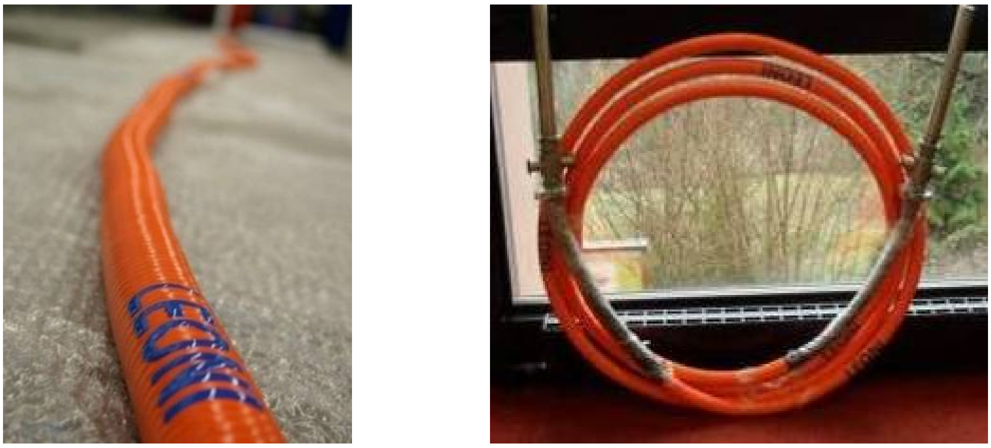

Figure 4: ***icefuel®*** **cable sample (outer diameter: ca. 40 mm; max. transport capacity: 100 – 200 kW_{LHV}; LEONI, Nuremberg).**

3.2 Infrastructure components

Micro structured heat exchangers (characteristic channel dimensions: 200 to 400 µm) generally exhibit several potential advantages for heat transfer applications with and without phase changes and especially in the context of the *icefuel*® infrastructure. First, heat transfer is very efficient which is of particular interest at low temperature gradients and very low temperatures (such as for LH2). Secondly, the hydrogen hold-up of micro heat exchangers is very low increasing the control dynamics as well as reducing potential hazards from leakages. A special challenge in the design results from the extreme physical properties of hydrogen (especially viscosity and interfacial tension) in the cryogenic state. Figure 5 shows various Micro Heat Exchangers that were developed and successfully tested on processing of hydrogen at different temperatures.

Figure 5: Various micro heat exchangers being developed for cooling, heating or other processing of hydrogen (IMVT, Karlsruhe).

Since LH2 has a specific exergy of more than 10.000 $kJ \cdot kg^{-1}$ recovering at least some of that potential technically would be worthwhile to improve energetic efficiencies as well as system economics. Different technical alternatives for exergy recovery were investigated and identified, such as liquefaction of nitrogen which could be used as a cooling shield (see figure 3). Another way is to implement thermoelectric generators into heat exchangers designed for the LH2 heat up prior to its utilization. So far, only few thermoelectrically active materials have been investigated for cryogenic applications. Figure 6 shows a micro structured heat exchanger equipped with a thermoelectric generator on the laboratory scale. The working principle has been tested and demonstrated successfully using liquefied nitrogen (-196 °C).

Figure 6: Lab scale micro heat exchanger equipped with a thermoelectric generator (DLR, Cologne and IMVT, Karlsruhe).

3.3 Miniplant

A miniplant has been designed and erected at the Institute of Micro Technology in Mainz (see figure 7). The objective is to test components that have been developed during the project, especially cable samples, on the technical scale and to provide scalable data for later field tests. Overall, four cable samples were successfully tested. Hydrogen throughputs (calculated as energy flows) are in the range of up to 30 kW_{LHV}.

The tests confirmed insulation performance results previously determined at the Bavarian Centre for Applied Energy Research (Wuerzburg) on the lab scale. Thus, specific heat inputs into the cable samples could be kept at ca. 1 $W \cdot m^{-1}$ during operation with LH2.

Figure 7: ***icefuel*® miniplant at IMM (Mainz).**

3.4 Safety assessment

Safety related consequences of cryogenic hydrogen releases from *icefuel*® cables were investigated both theoretically and experimentally in depth. The work focused on unconfined sonic hydrogen jets from small breaks without and with early ignition at different temperatures down to 30 K (see for example figure 8).

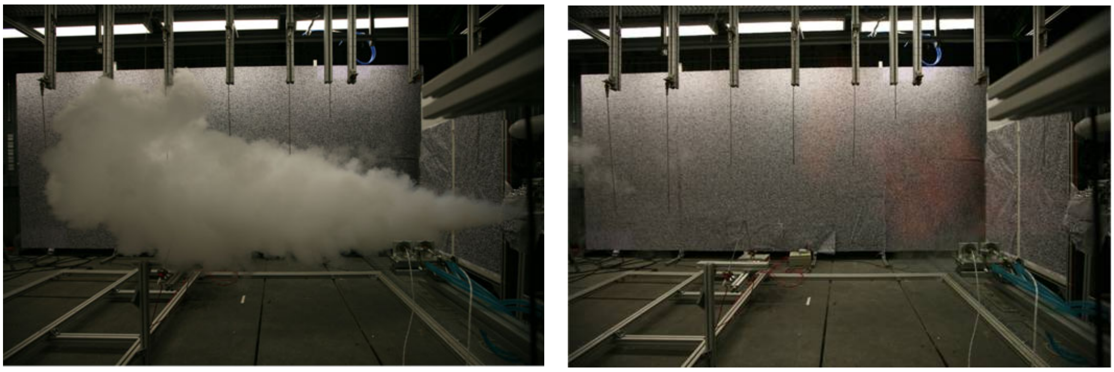

Figure 8: Pictures from cryogenic hydrogen releases before (left) and after (right) ignition (IKET, Karlsruhe).

Thermal loads, pressures as well as sound levels have been investigated for different parameters and compared to known limits for humans. All mechanical loads observed were uncritical. Investigation of thermal loads didn't show higher risk potential than for other energy carriers (e.g. natural gas, gaseous hydrogen). Overall, applying adequate technical and administrative safety measures would enable the safe operation of an *icefuel®* infrastructure.

3.5 Regulations, codes and standards

The TUEV SUED Industry Service (Munich) assessed different ways for approval of an *icefuel®* infrastructure. Currently, none of the existing regulations would be directly applicable. Based on the results in the safety investigations at IKET a newly to be defined regulation under the roof of the German Energy Industry Act is considered to be most promising. However, for the purpose of field tests, which are planned for a next development phase, existing regulations would still be applicable.

3.6 System economics

Assessment of the overall system economics at the current state of development is difficult since many system components (e.g. electrolysis, liquefaction, fuel cells) are still far from being technically and/or economically optimized. However, some qualitative statements can be made. As mentioned at the beginning, hydrogen is likely to play a major role in future energy infrastructures with high shares of renewable power despite the relatively low electric efficiency of the storage process. The questions will be how to store hydrogen and – in case of stationary utilization – how/where to reconvert it to electricity. The higher the amounts of energy to be stored (or: the longer the periods of time with excess or shortfall of renewable energy) the more attractive the storage of hydrogen as LH2 will be. Decentral utilization of hydrogen makes it easier to realize combined heat and power production. The worth of the co-generated heat depends on the alternatives for heat generation. Finally, several additional optimization potentials in an *icefuel®* system could be realized such as integration of superconducting wires into the *icefuel®* cable or utilization of the cold form the LH2 at the point of use.

4 Outlook

Based on the successful developments the project partners currently assess different alternatives for testing the *icefuel®* system on the field scale. Development activities in that context will include further hardware components such as junctions, sensors and actuators.

Acknowledgment

The scientific investigations and developments of this work have been carried out within the publicly funded research project *icefuel®* (BMBF, Bonn, FKZ 16SV2357). The authors would like to thank the German Federal Ministry of Education and Research for the support. More information: www.icefuel.eu.

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