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Potential of the Chemical Role of Hydrogen

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1 Summary

This paper reflects on the potential of the chemical role of hydrogen in the emerging early market applications within the field of fuel cells. Examples of the main polymer electrolyte membrane (PEM) fuel cell applications and of first products are presented together with some of the main players of this industry in an early development phase.

Due to the early stage of the market development, the role of innovation is discussed briefly: Technical innovation as a strict increase in performance is estimated to be more critical for the automotive fuel cell development with extremely stringent performance, durability and cost targets to compete against an existing and widely established technology.

Innovative business solutions are also needed to create traction in early market fuel cell applications that already meet the specific requirements of their niche markets. This business development activity is essential to establish, in the short term, the fuel cell technology as a credible alternative to traditional power supply.

Solvay [1] as a provider of specialty polymers together with Umicore [2] – a company specialized in catalysis and precious metals recycling – and their Joint Venture SOLVICORE [3] provide innovations, material and component solutions for the early market fuel cell applications of today and automotive fuel cell technology of tomorrow.

As governments around the globe are funding fuel cell development, in some cases, with very large resources, we may be on the verge of a quickening of market developments in some areas to be closely watched. The main activities are mentioned together with some of the principal industrial players and their regional spread.

2 Introduction

Hydrogen is widely seen as an important and clean energy carrier of the future [4]. Today hydrogen is mainly used as an industrial gas for chemical processes. The main production method for hydrogen is steam reforming of natural gas, in which by means of a catalytic reaction hydrogen is extracted from methane with CO_2 as the main by-product. Other ways to generate hydrogen are the widespread chlorine-alkali electrolysis reaction or polymerisation processes, in which hydrogen is released as a waste product. Therefore the main production sites for hydrogen are refineries and chemical plants. As hydrogen is used as a chemical gas also in other processes (e.g. reduction of metals), there is an industrial market with well established players such as LINDE (Germany) [5], AIR LIQUIDE (France) [6], AIR PRODUCTS (USA) [7] or IWATANI (Japan) [8].

With the increasing popularity of fuel cell technology over the last 10 years, the interest in hydrogen generation, infrastructure, storage and transport increased dramatically. Fuel cell driven vehicles or products will not be successful without the required hydrogen infrastructure and efficient ways to produce, transport and store hydrogen. One promising technology to produce hydrogen on demand from electricity is the reverse fuel cell or the so called PEM electrolysis. This technology offers the potential to produce hydrogen without any greenhouse gas emissions when it is combined with electricity from renewable sources [9].

In September 2009, the leading vehicle manufacturers in fuel cell technology - Daimler AG [10], Ford Motor Company [11], General Motors Corporation [12], Honda Motor Co., Ltd. [13], Hyundai Motor Company [14], Kia Motors Corporation [15], the alliance Renault SA [16] and Nissan Motor Corporation [17] and Toyota Motor Corporation [18] - issued a joint statement to the development and market introduction of electric vehicles with fuel cells [19]. This statement predicts the introduction of several hundred thousand vehicles in the years after 2015. Only one day later Daimler, Linde, Shell [20], Total [21], Vattenfall [22] and others signed a Memorandum of Understanding (MoU) together with the German authorities to establish a hydrogen infrastructure in Germany after 2015 [23].

Though the path for the commercial introduction of electric vehicles with fuel cells and the related hydrogen infrastructure seems to be clear, it will still require another five to ten years until this market will slowly emerge.

Until then, there are other interesting activities in the field of fuel cell technologies, which will be discussed in this paper. As the first so called early fuel cell markets already exist in several niches, several thousands of fuel cells are in the hands of consumers or industrial users today [24]. In early market applications the products are targeting specific competitive advantages, such as the reduction of system operational costs, increase of battery runtime or green minded consumer habits. These early markets and some of the relevant players are presented together with the potential of the technology for the specific niche market and its challenges.

3 The Emergence of Early Application Markets within the Field of Fuel Cells

The early application markets can be divided into four main groups of applications:

- alternative propulsion
- portable fuel cells
- stationary combined heat and power production (CHP), auxiliary power units (APU) and uninterrupted power supply or back up power systems (UPS)
- hydrogen generation via PEM electrolysis

Solvay and its Joint Venture SolviCore (Joint Venture with Umicore) provide innovations, material and component solutions for the above mentioned early market fuel cell applications of today.

3.1 Alternative propulsion

The drive train concept of fuel cell vehicles will not be a 100% fuel cell solution, but a hybrid concept which will combine the fuel cell as power generator and supply, a battery as power storage and supply and the electric engine to drive the vehicle [25]. For the classical automotive application the operational mode and the size ratio between fuel cell and battery are still under development. Nevertheless, it is expected that the fuel cell has to operate most dynamically to answer the requirements of the standard automotive drive cycles, which include start and stop routines under various condition. As this application will require further development time until commercial products will enter the markets, it will not be discussed here.

The situation is different for the so called “Alternative Propulsion” concepts. In these applications the achievements of the fuel cell development of the last decade and its advantages were combined with hybridization concepts and specific requirements of specialty vehicles such as buses, duty, specialty and material handling vehicles, boats and other light vehicles, which already used hybrid or electrified drive trains. For the early markets in this field, specific advantages of the integration of fuel cell technology lead to new clean solutions that in several cases also provide cost advantages during operation [26].

The number of fuel cell hybrid buses that were tested in the last years and are under operation today is constantly increasing and probably number above 100 today. Leading companies here are: TOYOTA and DAIMLER with their HINO [27] and CITARO [28] bus fleets which are operated in Japan, Europe and in the USA. Other bus manufacturers such as VAN HOOL [29] in Belgium are also testing fuel cell hybrid concepts by integration of fuel cells from stack manufacturers such as UTC [30].

The operation of fuel cell buses has many advantages: the infrastructure issue for hydrogen can be solved by a central filling station, the volume and weight of the hybridized drive train concept is carried by the large vehicle, the vibration and noise for the passengers are reduced, additionally, the buses are operating with zero emissions to the environment.

Tractors, garbage trucks, trains or other specialty vehicles basically have similar characteristics as discussed above for buses. Partnerships were developed between vehicle manufacturers and fuel cell companies to integrate the fuel cell hybrid concept into these vehicles. One example is the European initiative HYCHAIN [31], where under the lead of AIR LIQUIDE, fuel cells from its subsidiary AXANE [32] or other manufacturers were integrated into small transport or utility vehicles.

A success for the introduction of fuel cell technology into an existing market is the replacement of lead-acid batteries in the area of material handling. Especially in the USA large amounts of public funding money enabled forklift manufacturers such as YALE [33], RAYMOND [34], HYSTER [35] or CROWN [36] to integrate fuel cell systems from BALLARD/Plug Power [37, 38], NUVERA [39] or HYDROGENICS [40] to build several hundred forklifts and to set up their operation at several sites across the USA. The advantages are zero emission of the trucks, fast refuelling, less battery maintenance and charging time, which means more efficient operation of the truck fleet.

Activities in Europe in this field are taking off more slowly. Currently partnerships between European forklift and fuel cell manufacturers are in the early phase (e.g. HYDROGENICS and STILL [41]) and there is not yet a comparable funding activity to support the establishment of a European technology platform. In Japan TOYOTA and NISSAN already have been operating their own fuel cell technology in their forklifts since many years and started to announce the commercial introduction of their future products [42, 43].

The large boat and yacht market is a very interesting field for the clean and quiet fuel cell technology. Starting from CO_2 emission regulations for harbour manoeuvres to the reduction of noise and vibration of diesel gensets, that are used today to supply the boats with electricity, the advantages of fuel cells are obvious. One example for the integration of fuel cell technology into a sailing yacht is the ZERO-CO_2 YACHT project [44]. A hydrogen fuel cell that was developed in collaboration between PSA and the CEA is integrated into a sailing yacht from the boat manufacturer RM to provide the electricity for the electric engine of the yacht and eventually for the research lab, which is used during the research expedition to study pollution in the Mediterranean Sea. Another example is the development of generator type fuel cells by the VOLVO [45] subsidiary POWERCELL [46]. As one of the world's largest manufacturers of marine engines and generators, VOLVO is developing its market to the next level by reduction of emissions, noise and vibration.

The market for light vehicles is huge as it covers a broad range from leisure electric bicycles, scooters to medical wheelchairs or utility transport vehicles. These markets were also addressed in the European HYCHAIN program, in which e.g. AXANE fuel cells were integrated into electrical wheelchairs.

In all these areas of alternative propulsion it has been demonstrated that fuel cell technology can provide clean solutions together with economical feasibility. With increasing production volume and the expected cost reductions it is expected that these markets have a strong growth potential in the coming years.

3.2 Portable fuel cells

Portable electronics created several revolutions in people's lifestyle over the last decades. Portable music, video players, cameras and game consoles merged into smartphones, the latest mobile communication devices. People today are used to the support of electronic devices, but also to the necessity of chargers and charging times. At the same time, many technologies adopted electrical features or require electricity for their operation. Sometimes the power demand is served by large batteries, sometimes by small generators, which are often called Auxiliary Power Units (APUs).

For all these applications fuel cells can provide either more comfort, less weight or noise and emission free solutions, which in specific niche applications also reduce the operational costs dramatically due to reduced maintenance requirements.

The APU fuel cell market already exists. Though based on methanol as a very high density energy source – not based on hydrogen – the German company SMART FUEL CELL [47] has developed a range of portable power generators in the range of several hundred Watts. The portable generators are marketed under the name Efoy as APUs for recreational vehicles, as portable generators for remote electricity supply and as battery range extender for light electric vehicles. A similar product also serves as APU or generator for marine applications under the name MAXPOWER [48]. More than 15.000 of these units are in operation today while the market and the volume are constantly growing.

The introduction of the fuel cell as a battery runtime/range extender for long term low Watt power supply is the goal of the German company FWB [49]. Again methanol powered fuel cells are combined with a battery to utilize the high energy density of methanol inside of a tank to power towel machines, sensors or UPS tracking devices. These devices require very low level power supply in the Watt range over a time periods of several weeks or even months. Today the solution is the use of large batteries which cause very high operational or maintenance costs.

The introduction of small battery chargers for Li-Ion batteries based on methanol fuel cells was not successful over the last 10 years due to the limitations of the power density of the fuel cell systems. In 2010 the Swedish company myFC presented a tiny battery charger, which is supposed to hold enough energy and supplies sufficient power density to charge Li-ion batteries [50].

In the areas, in which limitations of battery runtime or long charging times are the cause for limitations to the use of portable electronics or any battery dependent device it has been demonstrated that fuel cell technology can provide clean and comfortable solutions together with economical feasibility. With increasing production volume, the expected cost reductions and increasing customer acceptance it is expected that the fuel markets will grow together with the markets of their applications.

3.3 Stationary CHP, APU, UPS

A fuel cell development program was started in Japan in the 1990s with the goal to supply private households with heat and electricity generated by residential fuel cell units. These units combine a reforming unit to convert a methane rich gas into a hydrogen rich gas, which is again transformed in a fuel cell into electricity and heat for the hot water supply. During a research phase about 100 field test units were installed and operated in the years 2002 to 2005. The commercial introduction of combined heat and power supply units (CHP) based on residential fuel cells has started in Japan. In collaboration with house manufacturers more than 7000 units were installed between 2005 and 2010. The suppliers of these systems are the Japanese companies TOSHIBA [51], PANASONIC [52], ENEOS [53] and TOYOTA. Funded by a large NEDO [54] program these companies were able to develop and establish the complete value chain for the technology in Japan. It is planned to continue the introduction of these systems with increasing volume in the coming years and to explore other markets for the technology.

There are no such programs in the USA and in Europe. In the USA companies tried to develop similar systems in different sizes over the last 10 years, but no commercial breakthrough of any system could be achieved. In the frame of the German CALLUX program [55] a few hundred systems will be installed in the coming years, which will demonstrate the integration of PEM fuel cell stacks from the Canadian company BALLARD by the British company BAXI [56] among other fuel cell technologies.

The chemical industry with its large scale production of Chlorine, NaCl and various polymers produces huge quantities of so called waste hydrogen [57]. In some cases the hydrogen is used in integrated processes or for its caloric value. In other cases the hydrogen is vented to the atmosphere as its use is not required or too cost intensive for the facility owner. In 2010 SOLVAY launched a project at its Solvin plant in Lillo (close to Antwerp, Belgium) to explore the potential of the utilization of such process waste hydrogen [58]. For this purpose a 1 MW fuel cell plant from the Dutch company NEDSTACK [59] will be installed to generate electricity and hot water for the facility. Together with its Joint Venture SolviCore, that is the supplier of the membrane electrode assemblies (MEAs) for the fuel cell, and NEDSTACK as system provider, SOLVAY will investigate and demonstrate the economic and ecologic potential of the fuel cell technology to recover waste hydrogen from chemical processes to feed back electricity and to reduce the carbon footprint of the Lillo facility.

In countries with a weak infrastructure for electricity and communication fuel cells have the potential to provide safe back up power supply for IT and telecommunication centers (remote power supply). Installations for these purposes are successfully operated In the USA and in India, more installations are expected to follow in the coming years in other developing, emerging or remote areas in the world [60]. The advantages of these markets are that the technical challenges for the fuel cells are relatively moderate, which leads to simplified designs that can meet the cost targets of the application. Main players in the USA are BALLARD with PLUG POWER, IDATECH [61] and others as system integrators, HYDROGENICS and NUVERA, Main players in Europe are HELIOCENTRIS [62] and RITTAL [63] as integrator of BALLARD stacks in Germany, AXANE and HELION [64] in France and NEDSTACK in the Netherlands.

The market for APUs for trucks and buses is motivated by strict regulations for emissions during idling times (e.g. overnight). Today the electricity for the cooling of truck loads or for the truck cabins is provided by the diesel engine in idle mode. As this is causing noise, CO_2 and other emissions VOLVO, one of the large truck producers in the world, is developing fuel cell APUs with a diesel reformer in its subsidiary POWERCELL.

AXANE is also developing a market for mobile power generators. With the background of its owner AIR LIQUIDE as a gas and hydrogen supplier these systems are operated with bottled hydrogen.

Due to emission reduction programs or interesting niche applications, new markets for fuel cells are being developed. New solutions are already in the market today with growing acceptance and success.

3.4 Hydrogen generation via PEM electrolysis

While fuel cells produce electricity and water, a reverse fuel cell reaction can be used to generate hydrogen and oxygen from water and electricity. This reverse fuel cell technology is called PEM electrolysis [9]. Compared to the well established technology of alkaline electrolysis the PEM electrolysis has significant advantages for several applications. The main advantages of the PEM electrolysis are the potential for a wide operation window and the high energy efficiency which results in very compact systems with a size reduction of more than 90% compared to alkaline systems.

Until recently the main market for PEM electrolyzers was the production of hydrogen for industrial use as process gas in chemical processes, in metal treatment (reduction), in the semiconductor industry and for generator cooling in power plants. The main manufacturers of PEM electrolysis systems for the so called on site hydrogen production are MITSUBISHI CORPORATION in Japan [65], PROTON ENERGY [66] and HYDROGENICS in North America and HYDROGEN TECHNOLOGIES (STATOIL, Norway) [67] and HELION (France) in Europe. This market has been slowly growing over the last 10 years and is becoming more and more attractive as the transport of hydrogen or its storage are expensive and ineffective for the overall energy and CO_2 balance.

In the last five years the first fueling stations were tested or installed in Europe, Japan and the USA which used PEM electrolyzers for the onsite hydrogen production.

In combination with renewable energy sources such as solar or wind energy hydrogen production can be realized without any CO_2 emissions. The first company that demonstrated such a green fueling station was HONDA in Torrance, California already in 2001. In recent years the utilization of electrolysis technology in combination with renewable energies becomes more and more relevant as it is seen as a solution to transform renewable energy into hydrogen as innovative energy storage method. In addition the technology could help to stabilize the electricity network which is facing more and more fluctuating power generation profiles due to the increasing percentage of renewable energy [68]. Under these conditions the advantages of the PEM electrolysis are obvious as relatively small systems can react dynamically to fluctuation of power input and generate hydrogen with high efficiency. The hydrogen can be used afterwards either in chemical processes or to produce electricity again in fuel cells.

4 Innovation in the Field of Fuel Cell Technology

Currently the emerging fuel cell industry is still highly fragmented. This is a major hindrance since it slows down development and achievements of economies of scale. Solvay as a provider of specialty polymers together with Umicore – a company specialized in catalysis and precious metals recycling – and their Joint Venture company SolviCore are committed to provide innovation, material and component solutions for the early market fuel cell applications of today and automotive fuel cell technology of tomorrow.

Technically this means that SOLVAY will develop new polymers and membranes and at the same time UMICORE will develop new catalysts with increased performance and durability, while SolviCore will integrate these new components into its MEA technology and establish the relevant mass manufacturing processes for the growing industry.

The joint effort of Solvay and Umicore can be seen as an example of open-innovation in the emerging fuel cell industry. Both chemical companies identified their potential for synergies in the development of the critical component MEA in 2005 and started a common activity in 2006. The next step is the joint development with other component and finally with fuel cell manufacturers to increase the partnerships along the supply chain.

The 1 MW project in Lillo is such an example which also includes the joint development of a new market. As Solvay has an interest in the utilization of waste hydrogen gas in its chemical plants and an interest in using SolviCore´s MEAs, the collaborative project with NEDSTACK is an approach to develop the technology and the market together.

Another example is SOLVAY´s collaboration with the UK based company ACAL [69]. ACAL´s innovation is in the new system architecture of their stationary fuel cells. These fuel cells are similar to the PEM fuel cells but have no cathode catalyst layer. Instead of the precious metal containing catalyst layer, ACAL realizes a proton exchange on the cathode with a reaction of a chemical catalyst which is pumped through along the cathode side of the membrane

(FLOWCATH®). To support the introduction of such new systems to the market by installation of a demonstration unit at a SOLVAY plant in the UK and in a collaborative approach between ACAL, SOLVAY and SOLVICORE will be the starting point of a new market development initiative.

SOLVAY and SOLVICORE are looking for such partnerships to overcome the hurdles of fragmentation and in the interest of boosting market development. Umicore also supports the activity with the service offer to develop financing and recycling models for the precious metals that are used in the fuel cells. Being the largest recycler of precious metals worldwide and one of the important suppliers of precious metal containing materials to the industry, Umicore expects from its experience in other markets, that the high fragmentation of the players along the value chain in the fuel cell market will probably merge towards those players that already have a large experience in handling, selling and trading of precious metals on the supplier side and towards those companies that are large and experienced enough to integrate large volumes of precious metals into their products [70].

As the path for fuel cell technology introduction in the automotive industry seems to be defined for the coming 10 years, innovation will have an important role to identify new applications in which fuel cells provide an operational, comfort, emission or cost advantage compared to existing energy solutions. At the same time governments, industrial users and consumers will have to be educated and informed about the new technologies, their status and their advantages in order to accelerate acceptance.

5 Fuel Cell Activities in Different Geographical Areas

The monitoring of fuel cell activities in the different geographical areas is important because it is currently the local applications of small efficient units that will drive development. The description that follows combines the view on main industrial players, technical status of the development and governmental programs, as these three topics are highly dependant on each other.

Asia probably has the strongest efforts in the area of fuel cell technology development, as this technology is identified as a key technology for the future of energy supply in countries like Japan, Korea, China and Taiwan. Here significant amounts of money are invested into the development of the complete value chain from materials, over components to systems.

The biggest and oldest program is the NEDO funding for the development of automotive fuel cells, residential fuel cells and hydrogen infrastructure in Japan [54]. Along the complete value chain, it has developed the key suppliers to a complete industry together with a handful of leading research institutes and universities as industry support. Among these players are TANAKA (catalyst) [71], ASAHI KASEI (membrane) [72], GORE-TEX (membrane and MEA) [73], TORAY (Gas Diffusion Layer – GDL) [74], MITSUBISHI RAYON (GDL) [75] and NOK-FREUDENBERG (GDL, Sealing, humidifiers) [76] in the field of materials and components. Among the important system OEMs are PANASONIC (residential and portable), TOSHIBA (residential and portable), ENEOS (residential), TOYOTA (residential, automotive and alternative propulsion), HONDA (residential, automotive and electrolysis), NISSAN-

RENAULT (automotive and alternative propulsion) and MITSUBISHI CORPORATION (electrolysis).

More recent is the launch of a funding program in South Korea, which funds Korean companies to establish the value chain and the technologies for a new Hydrogen Economy [77]. Main players in Korea are SAMSUNG (APU, portable, residential) [78], LG (portable, residential) [79], HYUNDAI/KIA [14, 15] and GS FUEL CELL (residential) [80]. The industry is strongly supported by the two major research institutes KIST [81] and KIER [82].

China and Taiwan also have funding programs with significant volume. Traditionally in China, a lot of effort and research money are invested in universities or institutes. R&D success is quickly followed by commercial initiatives supported by the government: the creation of new companies or transfer of the technology to big Chinese players. Given the large potential of these countries, it can be expected that they will play a major role in the fuel cell and hydrogen industry of the future.

India and other emerging economic powers are still shaping their programs but are committed to support the hydrogen economy.

Europe and many European countries launched their large funding programs in the recent years. The European Joint Technology Initiative (JTI) will distribute more than 400 million Euros to the 27 countries of the EU over the next 10 years. Today it is not clearly defined if the focus of the program will be research, value chain or demonstration project funding.

In addition, main government initiatives in Europe can be seen in Germany, France, UK, Belgium, Denmark and Norway.

Each country has specific important players for the industry. In Norway a subsidiary of STATOIL (Hydrogen Technologies) has a focus on hydrogen production. In Denmark, IRD [83] covers the value chain from MEA manufacturing to complete fuel cell systems. In Belgium activities of research institutes, universities and Belgian companies active in the field of fuel cells are supported in R&D and demonstration projects. Among the industry players are HYDROGENICS (hydrogen production), SOLVAY (fuel cell demonstration, polymers, membrane) and Umicore (catalysts and precious metals recycling). In the UK funding is provided to universities, institutes and industry players that develop materials and components such as JOHNSON MATTHEY (precious metals, catalysts, membrane, MEAs) [84] and system developers such as INTELLIGENT ENERGY (alternative propulsion) [85] and ACAL (residential) with their innovative fuel cell approach. France launched the seven year H2E program in 2009 to develop their hydrogen economy at a volume of about 200 million Euros [86]. It consists of 20 French companies and is lead by AIR LIQUIDE (hydrogen supply). Other major players are PSA (automotive) [87], MICHELIN (alternative propulsion, automotive) [88], AXANE (UPS, alternative propulsion), HELION (UPS, alternative propulsion, electrolysis), ARCELOR MITTAL (components) [89] and CEA (research, system development) [90].

The German program NOW was launched in 2008, the first funding initiatives were started in 2009 [91]. The program will distribute about 500 million Euros of funding to activities in Germany over 10 years in public private partnerships. The main focus is demonstration of fuel cell technology or pre-commercial activities to develop the emerging markets, but covers material, component and system related initiatives. Main players in Germany are DAIMLER (automotive), RITTAL (UPS), HELIOCENTRIS (UPS, educational), PROTON MOTOR (alternative propulsion) [92], SFC (APU, portable), MASTERFLEX (UPS, educational, alternative propulsion) [93], BOSCH (components, valves, compressors) [94], FREUDENBERG (GDL, sealing, humidifier) [95], SGL (GDLs) [96], SCHUNK (stacks, bipolar plates) [97], VICTOR REINZ/DANA (bipolar plates) [98], SolviCore (MEAs), FUMATECH (membranes) [99] and many institutes in the different federal states of Germany.

A large initiative is executed in the USA by the Department of Energy (DOE) [100], which supports the development of fuel cell technology since many years. Main players in the North America are GM (automotive), FORD (automotive), BALLARD (Vancouver, Canada – automotive, alternative drive train, UPS, residential) with its system integrators PLUG POWER and IDATECH, UTC (automotive, alternative drive train), NUVERA (alternative drive train, UPS), HYDROGENICS (Toronto, Canada – alternative drive train, UPS, electrolysis), PROTON ENERGY (electrolysis), BALLARD MATERIALS (GDL), 3M (catalysts, membrane, MEA) [101], GORE (membrane, MEA) [73] and DUPONT (membrane) [102].

6 Conclusion

The potential of hydrogen as an alternative energy source depends initially on the development of technical efficiencies in local, targeted and innovative applications. The successful partnering of the various stakeholders will enable the production of competitive market solutions. This activity will further drive development and education on the benefits of a future hydrogen infrastructure, as a credible solution to our clean energy requirements.

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