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Journal of Power Sources 154 (2006) 497–502

JOURNAL OF POWER SOURCES

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Short communication

Fuel cell commercialization: The key to a hydrogen economy

P. Zegers *

Tuindelle 28, 3090 Overijse, Belgium

Available online 1 December 2005

Abstract

With the current level of global oil production, oil reserves will be sufficient for 40 years. However, due to the fact that the global GDP will have increased by a factor seven in 2050, oil reserves are likely to be exhausted in a much shorter time period. The EU and car industry aim at a reduction of the consumption of oil, at energy savings (with a key role for fuel cells) and an increased use of hydrogen from natural gas and, possibly, coal, in the medium term. The discovery of huge methane resources as methane hydrates (20 times those of oil, gas and coal together) in oceans at 1000–3000 m depth could be of major importance. In the long term, the EU aims at a renewable energy-based energy supply.

The European Hydrogen and Fuel Cell Technology Platform is expected to play a major role in bringing about a hydrogen economy. The availability of commercial fuel cells is here a prerequisite. However, after many years of research, fuel cells have not yet been commercialized. If they will not succeed to enter the market within 5 years there is a real danger that activities aiming at a hydrogen society will peter out. In a hydrogen strategy, high priority should therefore be given to actions which will bring about fuel cell commercialization within 5 years. They should include the identification of fuel cell types and (niche) markets which are most favorable for a rapid market introduction. These actions should include focused short-term RTD aiming at cost reduction and increased reliability.

Keywords: Oil; Hydrogen; Fuel cells; Cost; Reliability; European union research

1. Limits to oil supply

Drivers for a long-term secure and sustainable energy supply are: (1) security of energy supply, (2) reduction of CO_2 (Kyoto) emissions and (3) pollution abatement.

In particular security of oil supply is a key issue as the share of oil in the final energy supply of the EU is 45.7%. The European oil supply depends for nearly 80% on the imported oil, of which a large and increasing part originates from the unstable middle east (where 65.4% of the global oil reserves are located); in particular transport is very vulnerable. Global oil reserves are sufficient for around 40 years with the current level of oil production [1] (Fig. 1). However, the global GDP is rapidly increasing with a subsequent increase in oil consumption. In a report by Goldman Sachs [2] (Fig. 2), it is expected that the GDP of the EU, the US and four major developing “BRIC” countries (Brazil, Russia, India and China) will have increased by a factor 7 in 2050. Oil reserves will therefore be exhausted in a much shorter time period.

We have come to the end of oil discoveries. During the decade 1990–2000 new oil discoveries amounted to only 25% of those during the period 1950–1960 [3] (Fig. 3). Today for every four barrels we consume one new barrel is discovered. We have used a bit less than half of the available oil and new cheap fields are not likely to be found.

In a publication in The Economist of 8/12/2001 [4] it is stated that where oil demand is continuously increasing, oil production has reached its maximum in 2003 and has started to decrease. It is expected that by 2020 there will be a gap between demand and supply of 65 million barrels/day and that the oil produced will come for nearly 100% from the middle east. Increased oil recovery from existing wells will only marginally improve this situation. Development of new fields will be expensive (e.g. deep sea drilling down to 2000 m in 2010) and the required investments for the next decade have been estimated by the IEA to be US$ 1 trillion. The key question is whether these investments, needed to develop new and more expensive oil wells, will be made in time. If this process is too slow, this will lead to shortages, high prices and unfriendly competition. In the long-term oil reserves will last much shorter than 40 years due to a strongly increasing demand in particular from emerging countries, such as India and China.

* Tel.: +32 2 6881098.
E-mail address: pieter.zegers@skynet.be.

0378-7753/$ – see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.jpowsour.2005.10.051

World Res. Gtoe	World prod. Gtoe	Reserves in years	EU	Former Sov. Union	Middle East	China	India	Australia	Japan	North Am.	S&C Am.
143	3.52	40.6	2.3%	7.5%	65.4%	1.7%	0.5%	0.3%	0.0%	4.8%	9.40%

Fig. 1. Global oil reserves 2001.

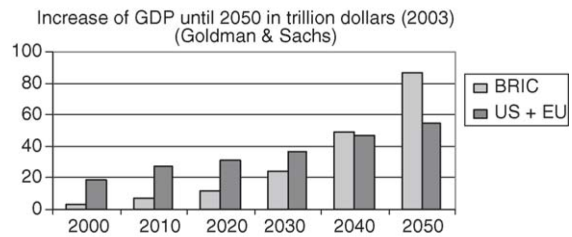

Fig. 2. Seven-fold increase of the GDP until 2050 for US + EU and Brazil + Russia + India + China (BRIC countries).

2. A secure and sustainable long-term energy supply

2.1. Alternative fossil fuels

The main fossil alternatives for oil are coal and natural gas. Contrary to oil the location of *coal* resources is very diversified; coal is cheap and global coal reserves are sufficient for 156 years of current coal consumption (not including sub-bituminous coal and lignite) [1]. However, the CO_2 emissions per MJ are two times higher than for natural gas and pollution abatement is very expensive.

Natural gas also has the advantage that the location of its reserves is more diversified than oil and that the remaining estimated ultimate resources (EUR), including those of which extraction is not yet competitive, are 40% higher and continue to increase whereas oil has leveled-off [5]. In addition huge methane resources, around 20 times those of oil, gas and coal together, have been discovered as *methane hydrates* in oceans [6]. They have the advantage that they are widely distributed in coastal areas of all continents (at 1000–3000 m depth). Methane hydrate crystals consist of a methane molecule surrounded by water molecules. These solids are stable at high pressures below 15 °C. Although a large part of the methane hydrates is too dispersed in the sediments, extraction of even a small part could improve global supply problems considerably. Techniques for commercial extraction may be ready in 10–15 years.

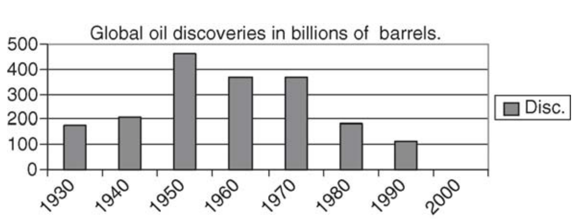

Fig. 3. The end of oil discoveries.

2.2. Options for a secure and a sustainable EU energy supply

The long-term aim is to come to a, largely, renewable energy sources (RES)-based energy supply. However, as this is not likely to be realized within 40 years, sustainable use of fossil fuels and possibly nuclear energy will be needed to bridge the gap. This results in two main scenarios which partly overlap and complement each other:

- Sustainable use of fossil fuels including CO_2 sequestration (2000–2030).
- A largely renewable energy sources-based EU energy supply (beyond 2030).

The first scenario aims at a reduction of oil and an increased use of natural gas (and possibly coal), RES and energy savings. A key issue is here the *clean production of hydrogen and electricity* from fossil fuels; in particular CO_2 capture and storage. It is believed that the cost increase of electricity and hydrogen due to CO_2 sequestration can, with an increased research effort, be reduced from current 50 to 20% in 10–15 years. The CO_2 storage capacity in the EU (aquifers, depleted oil and gas fields) is sufficient for 300 years of current EU annual emissions. As for *clean energy use*, research should focus on the development of cost-effective fuel cells which are expected to play an increasingly important role in bringing about increased security of energy supply and large energy savings of up to 50% in road transport (30% of the EU final energy) and 45% in low-grade heat production in the buildings and tertiary sector (40% of the EU final energy). *Fuel cells are key to a clean and secure energy supply based on hydrogen and electricity*.

A number of actions are aimed at decreasing the dependence on oil and to come to a secure and sustainable energy supply:

- Car industry is currently spending billions of Euros on research related to fuel cell driven cars, with the aim to replace oil by fuels from natural gas and RES, to increase the efficiency as compared to internal combustion engines by a factor two and to decrease greenhouse gas and other pollutant emissions to very low or zero levels.
- Oil companies become energy companies (Shell, BP), with large and increasing activities in fields, such as RES, hydrogen, etc.
- Both the EU and the US are giving strong political and financial support to an increased role of hydrogen from natural gas, coal and renewable energy.

In the EU actions which aim at bringing about a hydrogen economy, the recently created “EU Hydrogen and Fuel

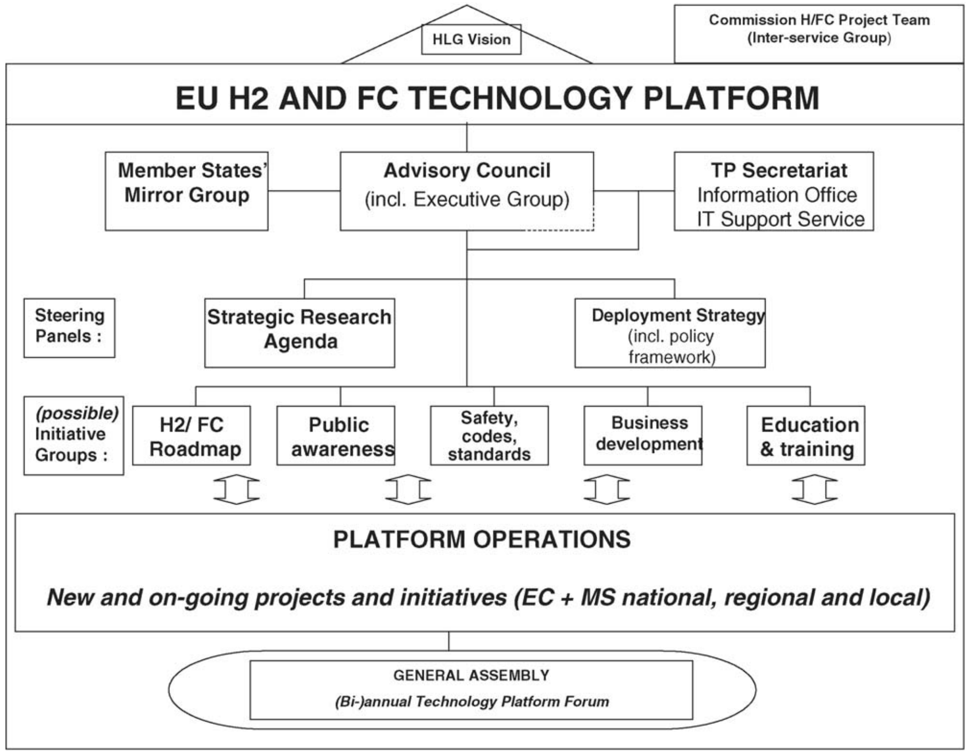

Fig. 4. The Hydrogen and Fuel Cell Technological Platform.

Cell Technology Platform", is expected to play a major role (Fig. 4).

3. The EU Hydrogen and Fuel Cell Technology Platform [7]

The EU Hydrogen and Fuel Cell Technology Platform is a comprehensive EU approach to bring about a secure and sustainable EU energy supply where hydrogen and fuel cells play major role. It started with setting up a *High Level Group* which prepared a vision report [8] which was presented in a conference in Brussels in June 2002. This conference in which the President of the EU Commission, three other commissioners and several national research ministers participated, had a high political profile and gave a clear political signal in support of these actions. They will include the creation of a European a political framework for fostering new hydrogen and fuel cell technologies. Also, a European partnership will be set up which aims to bring about a close collaboration between all main actors, such as manufacturers, energy producers, EU and national authorities, research institutes, universities, etc. This partnership will be steered by an *Advisory Council* which was nominated in December 2003. Its 35 members reflect the different organizations which participate in the Platform. The Advisory Council is assisted by: the *Member States' Mirror Group* with representatives of member states, which was established in February 2004, the *EC Project Team* in which eight EC Directorates General are represented (RTD, TREN, JRC, etc.) and the *Platform secretariat*. The Platform which was launched in January 2004 has two main activities: developing a *Strategic Research Agenda* and a *Deployment Strategy*. The *Strategic Research Agenda* was launched on 29 March 2004 in Petten in The Netherlands. Six working groups have been formed which will address: (1) hydrogen production; (2) hydrogen distribution and storage (safety, standards, etc.); (3) fuel cells for transport; (4) fuel cells for stationary applications; (5) portable fuel cells; (6) socio-economics. For these areas technical and non-technical barriers will be identified and priorities for research will be established. The development of a *Deployment Strategy* is a second major action. This will include transition lines for hydrogen and fuel cell technologies, safety, codes and standards and possible commercialization routes. New and on-going RTD projects in EU, National, regional and local programs will form an integral part of the above-mentioned activities. A number of *initiative groups* in support of the two main Platform activities may be set up, such as, hydrogen/FC roadmaps, public awareness, education and training, etc.

4. Slow fuel cell commercialization; a major barrier for an EU hydrogen economy

Bringing about a hydrogen economy is a major change in energy supply, which will take many years and is bound to encounter a number of barriers. As for hydrogen production (with reformers from natural gas and CO_2 sequestration) and hydrogen transport there seem to be no major technical problems although research is needed to reduce the cost. For hydrogen storage still much research needs to be done but even here there are promising options which may be commercially available in the near term. Investments in a hydrogen infrastructure will be huge but are likely to come about due to strong incentives, such as oil shortage and sustainability. *A major barrier is the slow progress of commercialization of fuel cells which are key to a hydrogen economy*. If they will not be available within 5 years there is a risk that the activities aiming at a hydrogen society will peter out. Major causes are high cost and insufficient reliability.

5. Cost

To be competitive with conventional systems, FC system costs should not exceed:

- €50 kW^{-1} for private cars;
- €200–300 kW^{-1} for lorries, buses;
- €400–600 kW^{-1} for portable applications;
- €400–600 kW^{-1} for cogeneration in buildings and power production.

The current costs of hand-made FC systems are around €3000–5000 kW^{-1} and it will be very difficult to reach the above-mentioned target costs; in particular for private cars. Although mass production may strongly reduce the cost of fuel cells, certain costs, such as for platinum and the membrane (for PEMFC) can probably not be reduced much by mass production.

5.1. Factors influencing cost

Fuel cells in general are suitable for *mass production* due to a limited number of different parts. In addition PEMFCs have the advantage of MEAs which are tailored to the needs of mass production and of low temperature manufacturing processes. The cost of MCFC and SOFC is expected to be considerably higher due to the high cost of high temperature (>700–1000 °C), often ceramic, materials and mass production processes. MCFC have the advantage, contrary to PEMFC and SOFC, of m^2 size cells which, due to economy of scale, can lead to cost reductions. The *power density* (power per cm^2 of cell surface) is an important fuel cell parameter and can vary between 0.1 and 1 W cm^{-2}, depending on the fuel cell type, i.e. thickness and ion conductivity of the electrolyte, the speed of the electrochemical reactions at the anode and cathode, etc. The power density is a key issue for the cost of fuel cells; low power densities require more cell surface per kW, resulting in an higher cost. Typical power densities are: PEMFC and planar SOFC [9]: 0.7–1 W cm^{-2}; DMFC: 0.05–0.1 W cm^{-2}; MCFC and tubular SOFC [10]: 0.14 and 0.18 W cm^{-2}, respectively. From the above data it can be concluded that, as for power density, PEMFC and planar SOFC have the highest potential for cost reduction. The cost of *Nafion membranes* in PEMFC ranges from €40 to 200 kW^{-1}; where the thickness of the membrane is an important cost factor. Expiring patents may reduce this cost in a not too far future. In addition new, cheaper membranes may become available. For PEMFC the *catalyst cost* is not to be a major problem; with a Pt load of 0.3 mg Pt cm^{-2} (which may be feasible in a not too far future) the Pt cost amounts to €8 kW^{-1}. For DMFC this cost would be around €400–800 kW^{-1}, assuming 2 mg Pt cm^{-2} and 0.05–0.1 W cm^{-2}. MCFC and SOFC have low cost catalysts. In case pure hydrogen is used a three-stage *fuel processor* is not needed, this will lead to additional cost reductions.

The potential for cost reduction is highest for PEMFC using pure hydrogen, as it has a high power density, is suitable for cheap mass production and does not need a reformer. It may be able to reach the low cost target of €50 kW^{-1} for private cars; this particularly in view of the strong commitment of the car industry to reach this target.

It should further be noted that if the cost, in the long term, could be reduced to €50 kW^{-1}, fuel cells could become very competitive for other applications with a higher allowable cost, such as buses, lorries, cogeneration and decentralised electricity production; provided that the problem of longer lifetimes can be solved. Taking into account the different factors which influence fuel cell cost an estimate is given in Fig. 5 of investment costs for different fuel cell types in the long term and their field of applications. Also current values of fuel cell compactness have been given. This in view of the fact that for road transport, compact systems of around 0.5 kW l^{-1} are required. Currently only PEMFCs could fulfil this condition.

6. Reliability

In addition to cost, insufficient reliability is a major barrier for fuel cell commercialization. Although the required lifetimes for major fuel cell applications are: 5000 h for private cars; 50,000–100,000 h for lorries and buses; 40,000–100,000 h for cogeneration in buildings and power production. A lifetime of 5000 h for PEMFC driven private cars with pure hydrogen seems to be achievable. For cogeneration in buildings with PEMFC (with natural gas reformers) lifetimes of only 1 year can currently be guaranteed [11] (due to both stack and non-stack components). For planar SOFC stacks, a strong voltage degradation results in a 40–50% decrease in efficiency after 10,000 h of operation (US DOE [12], Sulzer Hexis [13]). For tubular SOFCs and MCFCs the decrease of efficiency is very low: 1% (Siemens, Westinghouse [10]) and 3% (IHI, Japan [14]) per 10,000 h, respectively.

6.1. Factors influencing reliability

PEMFCs are vulnerable to *Pt catalyst poisoning* by S and CO impurities from reformate gases even at quantities as low as 2 and 10 ppm, respectively, the use of pure hydrogen would avoid this problem. The Nafion *membrane* in PEMFC is an excellent conductor of hydrogen ions provided that it is hydrated. *Water management* of the PEMFC is therefore key to reliable operation and both hydrogen and air entering the fuel cell must be humidified. This humidification must be carefully controlled as insufficient hydration could lead to irreparable damage by burn—out of the fuel cell. This makes the PEMFC vulnerable and research is needed to develop membranes which do not require hydration. In addition there are a number of *degradation processes* which are not well understood. In general there is a pragmatic approach to slow down degradation as much as possible by keeping voltage, temperature and hydration at constant levels and operating the PEMFC at part load. In this way

	Long term cost in €/kW	Applications	Compactness in kW/litre
PEMF + H2	50 - 100	Cars, buses, lorries, APU, portable, cogeneration, power prod.	0.5
DMFC	600 - 1000	Portable	0.1
Planar SOFC	200 - 300	Buses, lorries, APU, cogeneration, power production	0.05 – 0.2
MCFC, tub. SOFC	400 - 600	Cogeneration, power production	0.01

Fig. 5. Long-term cost estimates for different fuel cell systems.

average stack lifetimes of 3000–10,000 h are feasible. Also non-stack components limit the lifetime of the system. For propulsion of private cars, hybrid FC/battery systems using pure hydrogen would therefore be most appropriate. However, in order to reach target values of 40,000–100,00 h, basic research aimed at understanding degradation mechanisms in PEMFC is indispensable. In addition to most of the above problems DMFC have the problem of *methanol cross-over*. Also the low power density and high Pt load are drawbacks. For planar SOFC, the very high *voltage degradation* of 4–6% per 1000 h is a serious drawback and should be improved to at least 0.2%. Also sealing is a major problem which should be solved. Tubular SOFC and MCFC have demonstrated reliability with voltage degradations as low as of 0.1 and 0.3% per 1000 h, respectively. SOFC and MCFC often require very *long cold start-up times* of up to 10 h due to the brittleness of the components; also the *number of thermal cycles is limited*. *System reliability* will be improved by the use of pure hydrogen as a reformer is then not needed, this simplifies the FC system and also avoids start-up times of 2–10 min.

7. Savings, synergies, networks and virtual power plants

In addition to reductions of fuel cell investment costs there are a number of other factors which can contribute to a reduced cost of electricity and heat supply with fuel cells:

- Energy savings for fuel cell driven private cars can be as much as 50% as compared to ICEs, with subsequent cost reductions. During the life of a car these savings could amount to €8000 which is twice the cost of a fuel cell engine of 75 kW at €50 kW^{-1}; energy savings thus increase the allowable cost to €150 kW^{-1}. This under the assumption that the cost of hydrogen will the same as petrol. The hydrogen production cost in large reformers (100 MW) without CO_2 sequestration is estimated to be €5 GJ^{-1} [15], the cost of hydrogen transport by pipelines and compression to 700 bar can be estimated to be around €3 GJ^{-1} (US NREL [16]) and the current petrol cost without tax is around €10 GJ^{-1}. PEMFC fuelled with hydrogen from large reformers initially without CO_2 capture and underground storage is probably the best option for rapid market introduction. Even so the potential for reduction of CO_2 emissions could be as much as 67% (50% less CO_2 emissions with NG as compared to oil and 50% energy savings by the fuel cell).
- As compared to single fuel cells for stationary power production, fuel cells in networks offer mutual supply of electricity, peak demand could than be delivered by other fuel cells, thus allowing a reduction in size and investment cost. A reduction

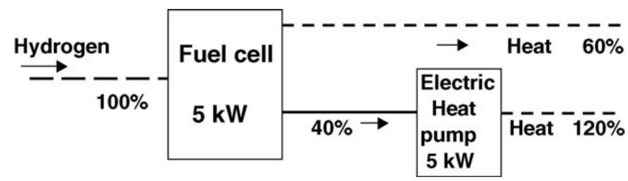

Fig. 6. Fuel cell driven heat pump system.

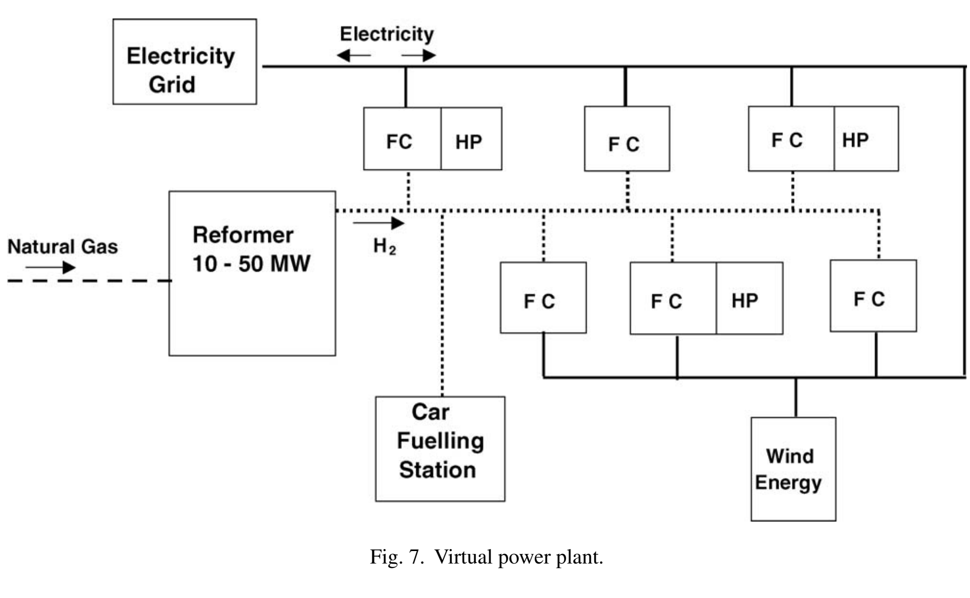

Fig. 7. Virtual power plant.

from 10 to 5 kW would reduce the investment cost per kWh considerably.

- The local use of waste heat from the fuel cell would lead to additional cost savings. However, it should be noted that only 15–25% of a household heat demand can be covered, due to the fact that heat supply and demand are often out of phase (e.g. in the summer) and that the heat/electricity supply ratio of a fuel cell is only 1.5, whereas a typical heat/electricity ratio for a single household is around 5; an additional NG boiler or heat pump will therefore still be needed.
- Use of the FC for also driving an electrical heat pump (Fig. 6) could bring about 45% energy savings (with a HP COP of 3 and use of the fuel cell waste heat).
- Moreover air conditioning in the summer is possible without additional investment costs.
- The FC + HP also leads to an increase of the annual production of kWh per installed kW; which further reduces fuel cell investment cost per kWh.

The production of pure hydrogen (down to ppm) from natural gas in reformers, is cheapest in large 10–100 MW size reformers due to economy of scale. On the other hand, in particular PEMFCs have a potential for very cheap mass production of small kW size units. A virtual power plant with centralized hydrogen production and a network of small interconnected fuel cells would minimize investment costs (Fig. 7). It would also have the advantage of cheap heat production with fuel cells by cogeneration or in combination with electrical heat pumps; which further reduces the cost per kWh. There is also a synergy due to the fact that the hydrogen infrastructure can be used both by stationary and transport fuel cell applications. Finally the VPP increases the capacity of power supply without an increase of the power distribution infrastructure and subsequent cost.

8. Conclusions

The slow progress of fuel cell commercialization is a major barrier for the introduction of a hydrogen economy. This in particular due to high cost and insufficient reliability. If they will not be available on the market within 5 years there is a risk that the activities aiming at a hydrogen society will peter out. A high priority should therefore be given to short and medium-term actions which can bring about a rapid FC commercialization, such as:

- A strong short-term action to identify niche markets for kW size fuel cell applications, which have high allowable costs and require short lifetimes (e.g. UPS, caravans and summer houses, yachts, portable applications, etc.).
- Give priority to cost reduction of hydrogen fuelled PEMFC systems for private cars (>0.5 $kW\,l^{-1}$), which require short lifetimes and relatively small systems. The strongly motivated car industry, which is spending billions of Euros on FC RTD, may succeed in reducing investment costs to the allowable cost of €50 kW^{-1}.
- In parallel, reliability problems related to long lifetimes (40,000–100,000 h) and cost reduction should be addressed for PEMFC in buses and lorries (€200–300 kW^{-1}) and for cogeneration (€400–600 kW^{-1}).
- Address cost reduction of tubular SOFC and MCFC for cogeneration and power production, which have demonstrated long life potential.
- Planar SOFCs still require much research to achieve a satisfactory reliability, solve sealing problems and reduce the cold start-up time to around 10 min.
- Cost reductions by synergies, FC networks, virtual power plants.
- Subsidies for fuel cell systems. Wind and PV have booming and rapidly increasing markets due to subsidies. In order to create FC markets, subsidies are indispensable at least for a limited period of up to 10 years.

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