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W. Tillmetz, U. Bünger

This document appeared in

Detlef Stolten, Thomas Grube (Eds.):

18th World Hydrogen Energy Conference 2010 - WHEC 2010

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

Proceedings of the WHEC, May 16.-21. 2010, Essen

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

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

Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010

ISBN: 978-3-89336-655-2

Development Status of Hydrogen and Fuel Cells - Europe

Werner Tillmetz, Zentrum für Sonnenenergie- und Wasserstoff- Forschung Baden-Württemberg (ZSW), Germany

Ulrich Büniger, 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 CO₂ 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 single most 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, CO₂-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)	85,000 (central)
	0.50 (decentral)	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 H₂ 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 H₂ liquefaction, electricity costs for H₂ liquefaction: 0.065 €/kWh, LH₂ trucking alone: 0.006 €/kWh (LHV).

2) Transport distance for LH₂ and CGH₂ 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 H₂ 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 be 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 CO₂-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.

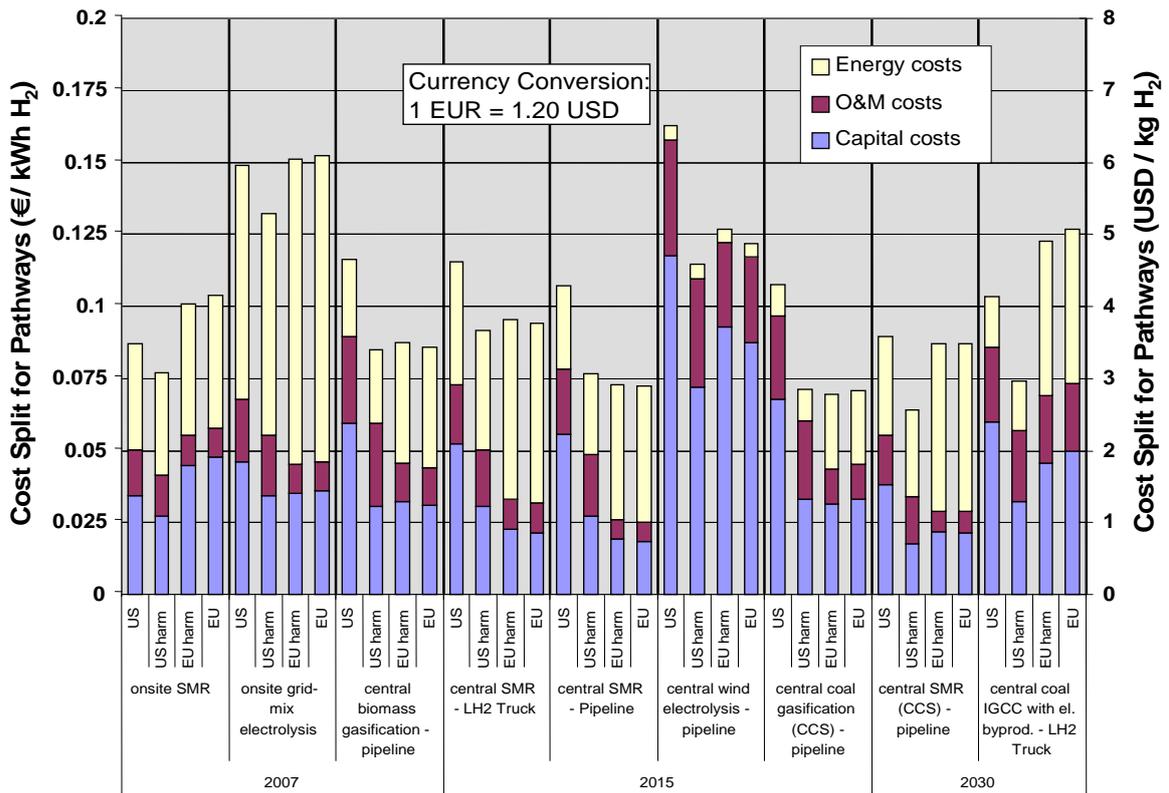


Figure 1: Well-to-tank cost analysis of representative hydrogen delivery pathways – benchmarking of European and U.S. studies [4].

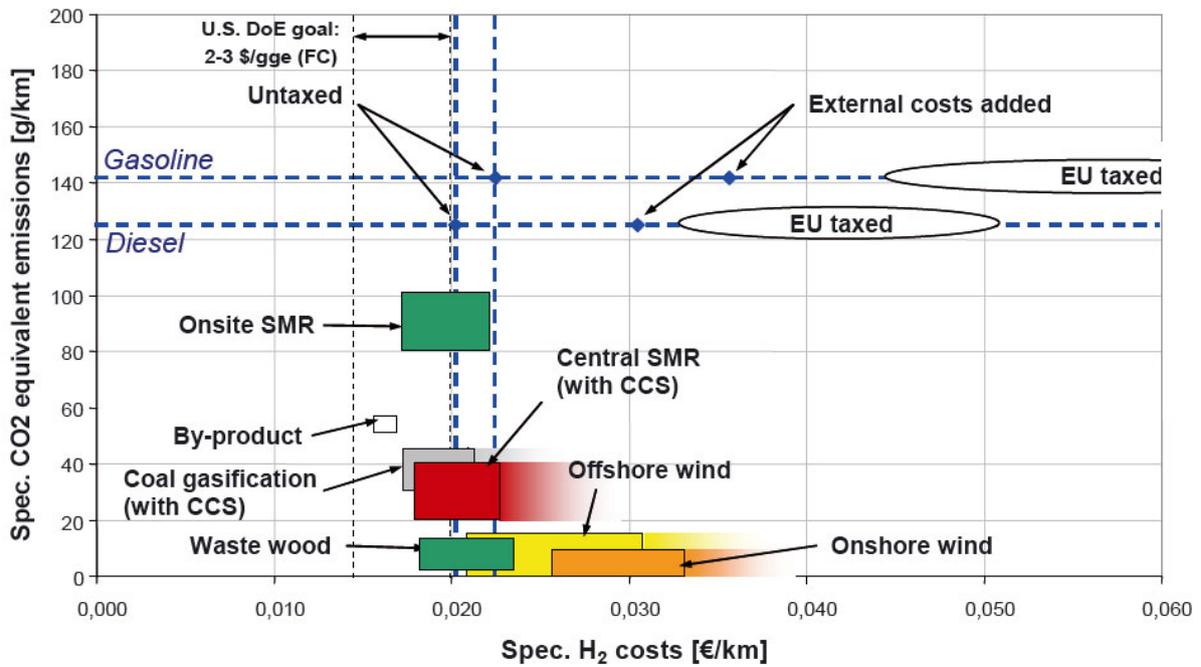


Figure 2: Spec. GHG-emission/hydrogen cost portfolio for Europe in 2030 [3].

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

A fuel cell, uses an external supply of chemical energy and can run indefinitely, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air). The source of hydrogen is generally referred to as the fuel and this gives the fuel cell its name, although there is no combustion involved. Oxidation of the hydrogen instead takes place electrochemically in a very efficient way. During oxidation, hydrogen atoms react with oxygen atoms to form water; in the process electrons are released and flow through an external circuit as an electric current. Fuel cells can vary from the Fuel Cells and Hydrogen for Green Energy in European Cities and Regions. A Study for the Fuel Cells and Hydrogen Joint Undertaking. Sponsor of the study Author of the study. The Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU). Roland Berger. Coalition of the study Regions and cities. Centre, Institute of Energy and Transport; Fraunhofer; Hydrogen Europe; HyER; Research Centre CEA; Research Center Rez; Scottish Hydrogen and Fuel Cell Association; Sir Joseph Swan Centre for Energy Research; STRING Network; University of Split. 3. Disclaimer. Status of fuel cell vehicle development. In this section, we summarize the status of fuel cell vehicle development as of mid-2017. Several groups of manufacturers are working together to co-develop fuel cell systems to reduce costs and accelerate production. BMW, Daimler, General Motors, and Kia have all announced that they plan to sell fuel cell vehicles by 2020. For heavy-duty vehicles, hydrogen fuel cell technology has been deployed in several demonstration and evaluation fleets. Table 1 shows a selection of hydrogen fuel cell. 4 U.S. Department of Energy, "Fuel Cell Technologies Office Accomplishments and Progress" (2016). <https://energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress>. The European Fuel Cells and Hydrogen Joint Undertaking launched the Hydrogen Roadmap for Europe highlighting all the opportunities hydrogen provides to decarbonise the gas grid and the transport and industry sectors, and its systematic role in the transition to a sustainable energy system. In turn, the certification scheme developed under the CertifHy project issued the first Guarantees of Origin for projects producing low-carbon hydrogen. In March 2019, Japan updated the Strategic Road Map for Hydrogen and Fuel Cells (initially published in 2017), confirming previous targets for mobility, the hydrogen supply chain and the domestic sector.