IEA Energy Technology Essentials

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The IEA Energy Technology Essentials are regularly-updated briefs that draw together the best-available, consolidated information on energy technologies from the IEA network

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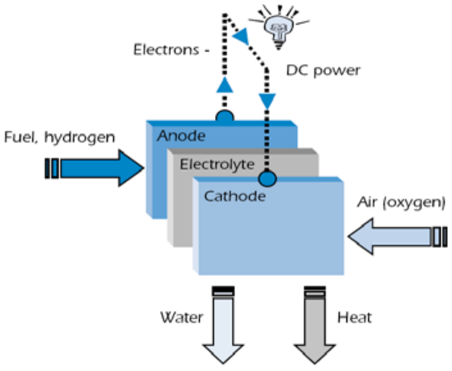
Fuel Cells

- **PROCESS & FC TYPES -** Fuel cells (FC) are electrochemical devices that use hydrogen (H_2), or H_2-rich fuels, together with oxygen from air, to produce electricity and heat. There are variants of this basic process, depending on FC types and fuels. Polymer electrolyte membrane FC (**PEMFC**) can be used either for powering vehicles or for stationary electricity generation. Sensitive to poisoning, PEMFC need pure H_2 input and produce no CO_2 emissions in the process. They operate at low temperature and offer efficiency of 35%-40%. Molten carbonate, solid oxide and phosphoric acid FC (**MCFC, SOFC, PAFC**) are used for stationary power and heat generation. MCFC are usually fuelled by natural gas. SOFC can be fuelled by either hydrocarbons or H_2. MCFC and SOFC operate at high-temperatures (respectively >650°C and 800-1000°C). SOFC offer the highest electrical efficiency (44%-50%) and can exceed 80% in co-generation mode. Direct methanol FC (**DMFC**) are the best option to replace batteries in portable devices, since methanol is easily transportable. Their efficiencies are between 15% and 30%. Fuel cell research focuses on improving performance and lifetime. Under fuel cell vehicle (FCV) operating conditions, the typical PEMFC lifetime is around 2,000 hours (100,000 km). In stationary applications, lifetimes may reach 30,000 hours. SOFC typical lifetimes are around 6000-8000 hours, with targets of 40,000-60,000 hours.
- **STATUS –**Fuel cell vehicles (FCV) mostly use PEMFC, which also cover some 70%-80% of the small-scale stationary FC market. MCFC and SOFC are expected to dominate the FC large-scale stationary use in the immediate future. SOFC currently represent 15%-20% of this market segment. Global FC production amounts to several thousand units per year, 80% for stationary and portable uses, the rest for FCV demonstration projects.
- **COSTS –** Prototype PEMFC may cost more than US $1800/kW (stack), but costs and technology are evolving fast. Mass production and technology learning could soon reduce costs to below $100/kW. If PEMFC stack costs fall to between $35 and $75/kW, and if costs of other components (H_2 storage system, electric engine) also fall, then the incremental FCV cost could be between $2,200 and $7,500 by 2030, assuming cost reductions of between 22% and 15% with each doubling of output. Today, 200-300 kW stationary MCFC or SOFC systems cost between $12,000 and $15,000/kW (50% for stack). Large-scale production is expected to reduce costs by a factor of ten in a decade.
- **H_2 STORAGE FOR FC VEHICLES –** H_2 storage in FCV is a major R&D issue. The compactness, driving range and cost of current options fall short of requirements. Gaseous storage at 350-700 bar and liquid storage at cryogenic temperature (-253°C) are commercially available, but energy-consuming and costly. Solid storage promises advantages and possible breakthroughs, but still needs much R&D.
- **POTENTIAL & BARRIERS –** FCV could gain significant market share over coming decades (up to 30% by 2050) if H_2 and FC costs are greatly reduced and if effective policies (incentives) are implemented to curb CO_2 emissions. The potential of stationary FC for distributed generation depends on feed-in tariff policies, on electricity and gas prices and on market competition from gas engines and small turbines. SOFC and MCFC – mostly fuelled by natural gas – are projected to account for 5% of global fuel cell capacity by 2050.

PROCESS & APPLICATIONS - Fuel cells (FC) are electrochemical devices that generate electricity and heat using H_2 or H_2-rich fuels, together with oxygen from air. They consist of an electrolyte sandwiched between two electrodes – an anode and a cathode (FC stack). Activated by a catalyst on the anode side, H_2 atoms split into electrons and ions. Electrons migrate to the cathode through an external circuit and generate electricity, while ions migrate through the electrolyte and reunite with electrons and O_2 on the cathode side, producing heat and water. There are variants of this basic process, depending on FC types and fuels. H_2-powered FC maximise the benefits of using H_2 as an energy carrier (e.g., efficiency, emission reduction), but most FC can run on other fuels.

■ **Polymer electrolyte membrane FC (PEMFC)** are suitable for either vehicles or power generation. They use a solid polymer membrane electrolyte and carbon electrodes, with platinum (Pt) as a catalyst. PEMFC are the best candidates for powering FCV as they operate at low temperature (80°C), offer short start-up time, high efficiency and good power density. Operational efficiency is well below the theoretical value of 65%, but it is more than twice that of typical combustion engines, with high sensitivity to operating conditions. Power density values are in practice around 2-3 kW/m^2. Higher values (4-6 kW/m^2) could be obtained if new membranes and more active cathodes emerge. High power density reduces the FC cost, but also increases energy losses and reduces efficiency. An optimum power density thus exists that minimises the energy cost, depending on the cost of H_2 and the FC.



Fuel Cell Concept

Current PEMFC are less durable than combustion engines. Membranes are sensitive to humidification. Anode catalysts are sensitive to poisoning by carbon monoxide (CO) and sulphur (S). They need rather pure H_2 input from electrolysis or from reforming, with extensive clean-up. They also need cooling to avoid overheating. Current research efforts focus on high-temperature membranes and new catalysts to improve performance and reduce costs. PEMFC can also be used for distributed power generation, with net efficiency of 35%-40%. Potential breakthroughs in H_2 distributed generation and synergies between PEMFC and PEM electrolysers could make PEMFC a very attractive option. ■ **Molten carbonate FC (MCFC) and solid oxide FC (SOFC)** are the best candidates for stationary power generation. MCFC are in most cases fuelled by natural gas or biogas. They cannot be fuelled by pure H_2 as they need CO_2 input. SOFC can be powered by either hydrocarbons or H_2. Both systems operate at high-temperature (>650°C and 800-1000°C, respectively) and neither need costly catalysts and external reformers when running on natural gas. Reforming is often needed when diesel fuel is used. Because of high operating temperature and long start-up time, they are not suitable for use in vehicles. High tolerance to hydrocarbons and CO makes SOFC a candidate for auxiliary power units (APU) in vehicles. MCFC use molten-carbonate-salt electrolyte, while SOFC use a ceramic oxide electrolyte. SOFC are produced with either tubular or planar stack configuration. The electric efficiency of current MCFC and SOFC systems is below 60%. Typical 250-kW MCFC systems can achieve 55% stack efficiency, 47% efficiency in alternating current (AC) and 42% net system efficiency including the auxiliaries. Operation at partial load results in slightly lower efficiency. If combined with gas turbines, MCFC-GT systems can achieve 47% to 53% net electrical efficiency, depending on size. Mostly fuelled by natural gas, current 100kW-150kW SOFC cogeneration systems offer net electrical efficiency of 44%-50% and overall efficiency exceeding 85%. Small SOFC for residential use have far lower efficiency. Prototype SOFC-GT systems achieve electrical efficiency of about 53%. In principle, they could attain electrical efficiencies of up to 70%. In co-generation mode, the overall efficiency of MCFC and SOFC depends greatly on the operating mode and on the heat-to-power demand ratio. Research seeks to improve FC durability and resistance to cycling load, high-temperature corrosion and poisoning. SOFC for operation at 600°C are being developed to permit use of low-cost stack materials. With improved tolerance to S, SOFC could be fuelled by coal-derived gas, since they use CO as a fuel. MCFC and SOFC are promising options for the market for combined heat and power (CHP) in buildings. SOFC could also be used in integrated coal gasification combined cycles (IGCC). ■ **Phosphoric acid electrolyte FC (PAFC)** and **alkaline FC (AFC)** are also used for stationary applications. PAFC were the first FC ever commercialised. They tolerate H_2 impurities and offer 37%-42% electrical efficiency (85% in co-generation). While many units are in operation, the potential market for PAFC is limited, since they are heavy, expensive ($4000-$4500/kW) and unlikely to become much cheaper. AFC were developed for power generation within the United States space programme. They use KOH solution as the electrolyte and non-precious metals as catalysts. They operate at 100-250°C (recent versions at 23-70°C) with efficiency of 60%. The alkaline electrolyte has low tolerance to CO_2, but AFC can also function in air with filters. ■ **Direct methanol FC (DMFC)** use methanol as a fuel. With low efficiency (15%-30%) and low power density, they are not suitable for mobile or stationary use. Because methanol is easily transportable, however, they represent an option to replace batteries in portable devices. In contrast, PEMFC offer limited benefits for use in portable devices, as H_2 storage offers no energy density advantage over batteries. Micro-SOFC are also being developed for portable use. Other FC concepts such as direct ethanol FC (DEFC) are under development for use in FCV. ■ **The lifetime of FC** needs to be improved. That of PEMFC depends on operating conditions (start-up temperature, humidification, fuel purity). Under operating conditions occurring in vehicles (cyclic loads, many starts-stops), the typical lifetime of PEMFC is around 2,000 hours (100,000 km). In stationary applications, lifetimes of up to 30,000 hours have been demonstrated. SOFC systems offer average lifetimes of some 6,000-8,000 hours, with best results attaining 20,000 hours. Target lifetimes are 3,000-4,000 hours for cars, up to 20,000 hours for buses (PEMFC), and 40,000-60,000 hours for stationary FC.

Tab.1 – FC Performance and Use

		PEMFC	SOFC	MCFC	DMFC
Operating Temp. (°C)		80-150	800-1,000	>650	80 100
Fuel		H_2	H_2, hc	ng, hc	methanol
Electrical Effic. (%)		35-40	<45	44-50	15-30
Applications		FCV Power	Station. Power	Station. Power	Portable Power
Lifetime (h)	FCV	2,000	6,000	8,000	na
	Power	30,000	20,000	20,000	
Target lifetime (h)	FCV	4,000	40,000	40,000	
	Power	20,000	60,000	60,000	na

STATUS – Several thousand FC systems are produced per year. Most are for small stationary units, several hundred for large stationary systems and several hundred for car and bus demonstration projects. Total installed FC power capacity is some 50 MW. Sales amounted to some $350 million in 2004. Stationary systems in operation world wide number roughly 3,000, including more than 2000 small units (0.5 kW-10 kW) and some 1000 large units (>10 kW). A number of additional small units are being installed for remote applications and telecommunication. PEMFC are the choice technology for the transportation sector but they also represent 70%-80% of the current small-scale stationary FC market. While PAFC have been pioneering for the large-scale stationary market, MCFC and SOFC are now the reference options in this sector. They are used in niche markets (back-up, highly reliable or remote power generation). SOFC represent 15%-20% of the stationary market, but their share is expected to increase. DMFC appear to be close to enter the market for portable devices. More R&D is needed for PEMFC in transport.

COSTS – ■ The cost of prototype **PEMFC** stacks may currently exceed $1,800-$2,000/kW, but producers are confident that mass-scale production for vehicles could reduce the cost to below $100/kW. In order to compete with combustion engines, however, the cost of PEMFC should be lower than $50/kW. Improved designs and materials are required, along with higher power density. As high efficiency compensates for higher vehicle cost, vehicles with high annual mileage such as buses, delivery vans and forklifts represent niche markets where FC could be competitive at costs of $135-$200/kW. Technology and cost projections for FCV are a matter for debate. A discussion of cost breakdown and projections for PEMFC systems is provided below, with cost details in Tables 2 and 3. ■ **Polymer membranes** (e.g., nafion) working at less than 80ºC need a Pt catalyst, which is expensive and sensitive to poisoning. Current costs can reach $800/m^2 ($250-$300/kW), but large-scale manufacturing would reduce this cost to $50/m^2. New materials (sulphonated plastic, ormosil), working at higher temperature and with less sensitivity to poisoning, promise technical breakthroughs and cost reduction. ■ **Electrodes** and bipolar plates currently dominate the FC cost prototype, as they are manufactured manually. Industrial production is expected to bring costs down by more than a factor of ten. Electrodes cost may be reduced from between $1,500 and 2,000/m^2 to $150/m^2 through mass production and new technologies that require less Pt. Current systems require 0.6-0.8 mgPt/cm^2, equal to around 1g/kW. Gas diffusion layer (GDL) technologies may result in better catalyst utilisation, thus reducing Pt needs. The goal is to arrive at 0.2 mg/kW. Assuming a Pt price of $10-$30/g, then the Pt cost would be $2-$6/kW. This is not a dominant cost for current FC, but it could be critical in the future, to reduce FC costs below $50/kW. Global availability of Pt could also be decisive. Assuming 0.2 g Pt/kW (20 g per vehicle), 100 million FCVs per year would require 2,000 tonnes of Pt per year; that is ten times current annual production. Analysis by Pt manufacturers shows that growing demand could be met by increasing production and recycling. but lowering Pt use or using new catalysts is of primary importance. ■ **Bipolar plates** are currently made from mouldable graphite-polymer composites or coated stainless steel. Using industrial injection-moulded plastics (carbon polymers) and low-cost steel alloys could dramatically reduce current costs. With production of one million plates per year, costs of carbon bipolar plates could drop to between $8 and $18/kW. While these improvements combined could meet the target of $100/kW, further reductions to below $50/kW would require higher power density (which limits efficiency and durability) and new materials and technologies. ■ Costs of other FCV components are also expected to fall. The **balance of plant** (BOP) including inverter,control electronics, humidification, H_2 and air pressurisation, cooling systems) could drop from between $45 and $55/kW to less than $15/kW; the **electric motors** from $25/kW to $15/kW. The most expensive single components are still the **converter,** the **batteries** to capture re-generative braking energy and cope with large variations in the DC-input voltage ($2,500) and the **$H_2$ storage system**. If the PEMFC stack cost dropped to $35-$75/kW by 2030 and the other components also cost less, it is estimated that the incremental cost of a FCV over a conventional vehicle could range between $2,200 and $7,500. The estimates assume a technology learning rate of between 0.78 and 0.85, equivalent to cost reductions of 22% and 15%, respectively, with each doubling of production. These values are within the range assumed for other new technologies. It is estimated that the cost of the basic materials for a FC drive system would account for some $20-$25/kW. ■ For **stationary MCFC and SOFC** systems, the cost of prototype or small-scale production of 200-300 kW units is between $12,000-$15,000/kW, the FC stack accounting for 50% of this. Large-scale production and technology learning are expected to reduce the cost to between $1,500 and $1,600/kW. These systems could become economically competitive in a few years, notably for distributed power generation.

H_2 STORAGE FOR FCV – On-board H_2 storage for vehicles is challenging and may have significant impact on H_2 infrastructure and standards. The target is to store 4-5 kg of H_2 (a drive range of some 450 km) while minimising volume, weight (gravimetric density >5-6 wt.%), storage energy, refuelling time, costs, and H_2 on-demand release time. To compensate for the low energy density per unit of volume, H_2 storage requires energy-intensive compression at 350-700 bar or liquefaction at -53°C. Current commercial options do not fully meet compactness and cost requirements. Both gaseous and liquid storage of H_2 need more space than energy-equivalent gasoline, also more costly tanks. Storage in solid materials may offer decisive advantages (smaller volume, low pressure and energy input) but development is still in progress, with a number of materials under investigation. On-board reformers to produce H_2 from fossil fuels also proved to be very challenging and expensive. ■ **Gaseous storage** in carbon-fibre composite (CFC) tanks at 350 bar is commercially available, but 700-bar tanks require new standards and certification in most countries. Main issues include cyclic loading, lifetime, cost and user's safety perception. Electricity for compression claims roughly 12% of the H_2 energy content (LHV). Tank costs may reach $2,500-$3,000/kgH_2. Large production promises costs below $500-$600/kg. The basic material (CFC) has a major impact on costs. Assuming a target cost of $180-$220/kg H_2, a 5-kg tank for a 75-kW FCV would cost some $12-$15/kW. An alternative under investigation consists of glass micro-spheres filled with H_2 via permeation at high pressure and temperature (350-700 bar, 300˚C). Gas is retained at room temperature and released at 200-300˚C. ■ **Liquid storage** at -253°C permits high gravimetric density. Target values are 20 wt%, including tank weight, insulation materials and systems to recover boil-off losses. Today's values are in practice around 5wt%. Electrical energy for liquefaction is around 30%-35% of H_2 energy content. An alternative is to use borohydride ($NaBH_4$) solutions that release H_2 through catalytic reaction ($NaBH_4 + H_2O > 4H_2 + NaBO_2$). The main issue here is the need to regenerate $NaBO_2$ into $NaBH_4$. ■ **Solid Storage** - The most developed materials for solid storage are metal hydrides with storage potential exceeding 8 wt%. (IEA HIA, 2005). New materials such as complex hydrides and alanates could gain appeal in the future. **Carbon nano-tubes and graphite nanofibres** attracted much attention some years ago but their expected storage performance of 30-60wt% has not been confirmed. **High-surface materials** such as zeolites, metal organic frameworks (MOF) and clathrate hydrates are in early stage of development. The question is whether they can be engineered to store significant amounts of H_2 at suitable temperatures. **Rechargeable hydrides** have been investigated at length and their potential is well known. Elemental hydrides are too stable (or too unstable) at operating temperatures. Alloys and intermetallic compounds have low gravimetric density (< 2.5 %wt.). Nano-crystalline and amorphous hydrides suffer from unsuitable storage capacities and release temperatures. **Complex hydrides** (alanates and borohydrides) are promising options requiring further development. $NaAlH_4$ alanate, for instance, offers favourable kinetics with reversible storage at around 4-5wt%. R&D focuses on catalysts to improve performance. Borohydrides ($LiBH_4$) have higher capacity than alanates, but H_2 release reversibility is more difficult. **Water-reactive chemical hydrides** can be handled safely in the form of mineral-oil slurry. They release H_2 through water injection into slurry without heat input. Theoretical storage is around 5-8wt%. MgH_2 is likely to offer the best performance/cost combination. The key issue is the cost of re-converting the spent hydroxide back into the hydride. **Thermo-chemical hydrides** such as ammonia borane are potentially suitable for H_2 storage, but the reaction is not reversible (off-board regeneration).

POTENTIAL & BARRIERS - According to *Prospects for Hydrogen and Fuel Cells* (IEA, Dec. 2005) and *Energy Technology Perspectives* (IEA, June 2006), H_2/FCV could gain significant market share over coming decades, so long as H_2 and FC costs can be reduced significantly and if effective policies are implemented for reducing CO_2 emissions. H_2 production costs should be reduced by a factor of 3-10, depending on feedstock and process, and PEMFC cost by a factor of 10. In addition, emission reduction incentives between \$25 and \$50/tCO_2, depending on fossil fuel prices, could render emerging technologies more economically attractive. Under these conditions, H_2-powered FCV could take a 30% share (700 million cars) of the passenger car market by 2050. Under less optimistic assumptions, FCV are unlikely to gain significant market share. Alternative technologies and fuel options such as natural gas, biofuels, hybrids or electric-battery vehicles could play a more important role. The potential of stationary FC also depends on policies (feed-in tariffs) and on electricity and gas prices, while also facing market competition from gas engines and small turbines. SOFC and MCFC, mostly fuelled by natural gas, are expected to respond to demand for combined heat and power in buildings, reaching some 200-300 GW of installed capacity by 2050 (or 5% of global capacity).

Data Confidence – Fuel cells R&D is rapidly evolving with large investment by the private sector. Information on FC performance and costs is sensitive. The above data basically refer to a detailed assessment published by the IEA in December 2005. More recent information and technical developments suggest slightly downward revisions of cost estimates.

Table. 2 - Cost Projections for PEMFC Stack

	Prototype		Mass Production		Target	
	$/kW	%	$/kW	%	$/kW	%
Membrane	250	14	14	16	13	25
Electrode	710	39	50	49	24	48
Bipolar pl.	825	45	30	29	9	17
Pt catalyst	25	1	3	3	2	4
Peripherals	8	0	1	1	1	2
Assembly	8	0	2	2	2	4
Total	1826		100		50	

Table. 3 – Cost Projections for PEMFC Vehicles (80kW)

	2005	2010	2030 optim.	2030 pessim.
PEMFC stack $/kW	1800	500	35	75
Storage700 bar , $	4000	2000	900	2000
FC stack, k$	144	40	2.8	6.0
Electric engine, k$	1.9	1.7	1.2	2.03
H_2 FCV, k$	167	61	22	27
Conv. vehicle, k$	19.5	19.5	19.5	19.5
H_2 FCV, $/kW	1875	545	60	125

Tab. 4 – H_2 Storage Options for Fuel Cell Vehicles

Current Options	Gas storage (C-fibre vessels)	Liquid storage (cryo-tanks)	Solid storage (metal hydrides)
Weight (wt.% H_2)	4 (6)	4-5 (20)	8?
Volume (litres)	240-160	120-130	60-80?
Press./temp. (bar/C)	350-700/ room temp.	1 bar/ -253 C	10-60 bar/?
Cost ($/kg H_2)	600-800	700-800	?
Energy (%H_2 LHV)	22-30	60	Low
Status	Commercial	Commercial	R&D
Pros	Temp., refueling time	Vol., pressure, refueling time	Vol., pressure, energy, H_2 purity
Cons	lifetime, vol., cost, energy	lifetime, boil-off, cost, energy	lifetime, weight, reversibility, time
Alternative options	Glass micro-spheres	$NaBH_4$, (C_7H_{14}, C_7H_8)	alanates, borohydrides, th.-hydrides

Further Information - www.iea.org; www.iea-afc.org; www.iea-hia.org; www.iphe.org; www.hfpeurope.org; *Prospects for Hydrogen and Fuel Cells* (IEA, 2005); *Energy Technology Perspectives* (IEA, 2006); *Hydrogen Production and Storage* (IEA HIA, 2005); *Hydrogen Economy: Opportunities, Costs, Barriers and RD&D Needs*, NRC (2004)