IEA Energy Technology Essentials

ETE 05

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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Hydrogen Production & Distribution

- **PRODUCTION & COSTS–** Hydrogen (H_2) is an energy carrier. It can be produced from all forms of energy and used for power generation or as a transport fuel, mainly in association with fuel cells. Natural gas and coal are currently the cheapest sources of H_2 and will remain so. Because production processes release CO_2, however, CO_2 capture and storage (CCS, ETE01) are vital to reduce emissions. H_2 production from renewable and nuclear energy will need more R&D and more time to enter the market. Decentralised H_2 production is the best choice for market uptake and for avoiding costly distribution infrastructure. But it is less efficient and costs more than large-scale, centralised production. The cost of decentralised H_2 production may exceed US \$50/GJH_2[1] today. Over the coming decades, improved technologies could provide fossil fuels-based H_2 at \$10-15/GJ, including the cost of CCS.
- **DISTRIBUTION –** Because of the low volumetric energy density of H_2, its distribution for energy use is rather expensive and energy-intensive. Investment and pumping-power requirements are greater than for natural gas. Large-scale H_2 distribution by pipeline adds \$1-\$2/GJ to H_2 production costs. Distribution of liquid H_2 is more costly (\$7-\$10/GJ) as energy is needed for liquefaction at -253°C. Refueling stations may add \$3-\$9/GJ to H_2 costs.
- **STORAGE IN FUEL CELL VEHICLES (FCV) –** On board H_2 storage presents R&D challenges (see ETE06, *Fuel Cells*). The compactness, driving range and cost of current options do not yet meet the requirements. Gaseous storage (350-700 bar) and liquid storage (-253°C) are commercially available, but energy-consuming and costly. Electricity needed for gas and liquid storage represents, respectively, some 12% and 35% of the H_2 energy content. The tank costs \$3,000-\$4,000 per vehicle. Solid storage promises potential breakthroughs, but much R&D is needed.
- **INFRASTRUCTURE –** Global investment to supply H_2 to the world's transport sector could be in the range of several hundred billion dollars over several decades (\$0.1-\$1.0 trillion for pipelines and \$0.2-\$0.7 trillion for refueling stations). This level of investment is not insurmountable in the long term, but building infrastructure today is premature because key H_2 technologies that may have an impact on infrastructure are still under development.
- **POTENTIAL & BARRIERS–** H_2 could gain significant market share in the transport sector if costs of production, distribution and end-use technologies (e.g., fuel cells) decrease according to expectations, and if strong policies are put in place to reduce CO_2 emissions. Under favorable assumptions, H_2 could be entering the market around 2020 and powering some 700 million fuel cell vehicles by 2050 (30% of projected global fleet). Besides costs, other barriers to H_2 use for energy applications include dedicated infrastructure needs, as well as competition with other emerging technologies and fuel options such as biofuels and battery-electric vehicles. However, since no single fuel or technology is likely to meet fast growing demand for clean transport fuels, various options are expected to play complementary roles in diversified regional markets.

PROCESSES & COSTS - Hydrogen (H_2) is an energy carrier that can be obtained from different sources: fossil fuels (natural gas reforming, coal gasification); renewable and nuclear energy (biomass processes, photo-electrolysis, biological production, high-temperature water splitting); and electricity (water electrolysis). If H_2 is produced from renewable and nuclear energy, or from natural gas and coal with CO_2 capture and storage (CCS), then it can be largely carbon-free, thus helping to reduce CO_2 emissions and diversify the energy supply. If H_2 is produced by water electrolysis, emissions are created by associated upstream electricity generation. At present, H_2 is produced largely from fossil fuels without CCS (48% from natural gas, 30% from refinery/chemical off-gases, 18% from coal, the rest from electrolysis). Most of today's production (some 65 million tonnes per year) is for captive use in the chemical and refinery industries. In the future, H_2 could be used for power generation and in transport by fueling gas turbines, fuel cells and combustion engines. Used in FCV, H_2 could significantly increase efficiency and emission reduction in transport. However, using H_2 for energy applications requires more efficient, less costly production processes, ideally with no CO_2 emissions. Decentralised production is the best choice for market uptake as it minimises the needs for distribution infrastructure. But it is less efficient than large-scale, centralised production, and it makes CCS impractical.

Some 140 H_2 refueling stations world wide fuel 400 FCV and 100 buses for demonstration projects

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(1) For comparison: oil at \$60/bbl ≈ \$10.5/GJ; gasoline at \$2.5/gge ≈ \$20/GJ; 1 GJ ≈ 8.3 kg H_2LHV; 1kg H_2 ≈1 gge

■ **Electrolysis** is a well-known electro-chemical process to split water into H_2 and oxygen (O_2) using electricity. Alkaline electrolysers with potassium hydroxide (KOH) electrolyte are commercially available. Efficiency is a key parameter for electrolysis, as costs are largely determined by electricity costs. Best-practice efficiency could be higher than 85% (GJH_2/GJ_{el}), but commercial devices achieve between 55% and 75%. New advanced electrolysers may approach the upper limit. At high temperatures, heat consumption increases while electricity needs decrease. High-temperature electrolysis (800ºC-1,000ºC) may therefore offer higher efficiency, in particular using residual heat. Also, high-pressure electrolysis can make H_2 pressurisation unnecessary and improve efficiency. New electrolyser concepts are based on fuel cells working in reverse mode. Small-scale polymer electrolyte membrane FC (PEMFC) electrolysers (60°C-80°C, 15 bar, 50% efficiency) are commercially available. Solid oxide FC (SOFC) electrolysers functioning at 700°C-1,000°C need more research. Current electrolysis costs are typically above $30/GJ$H_2$, but could drop to below $20/GJ (including pressurisation) over coming decades, assuming electricity at $35/MWh and 80% process efficiency. Use of off-peak electricity and large-scale plants may reduce costs, although the cost of CCS is expected to increase the cost of electricity. ■ **Natural gas reforming** is a mature technology used in the refinery and chemical industries for large-scale H_2 production. Small-scale reformers are currently used in demonstration H_2 refuelling stations (decentralised production). Reforming options include catalytic steam methane reforming (SMR), partial oxidation (PO) and other variants under development. In SMR, methane reacts with steam at 700°C-850°C to produce syngas, a mixed H_2 and carbon monoxide (CO) gas. CO is then converted into CO_2, producing additional H_2 by water-gas shift reaction. In the PO process, methane reacts initially with pure O_2 to provide syngas. SMR offers efficiencies of up to 80%-85% in large-scale units (excluding H_2 compression). If residual steam is re-used, total efficiency may be higher. Small units have lower efficiency (at least 10-15 percentage points lower) and higher unit costs. Producers have recently much improved the compactness of small-scale reformers (10x3x3m) and their capacity (5.5-7.5 GJ/hour), but further R&D is needed to reduce costs and increase efficiency. H_2 compression and CCS (eventually, in large units) may each further reduce net efficiency by some 5-10 percentage points. CCS in small plants is probably not practical. At current natural gas prices, ($6-$9/GJ), the cost of H_2 from natural gas reforming ranges from between $10 and $15/GJ$H_2$ (in large-scale production for captive use) to more than $30/GJ, with high sensitivity to natural gas prices, processes and economy of scale. Small-scale decentralised production may exceed $50/GJ. Compressed H_2 in tubes may cost $90-$100/GJ (delivered). Assuming natural gas at $3-$4/GJ, cost projections for natural gas reforming range from $6 in large plants to $10-$12/GJ H_2 in small plants (*Prospects for Hydrogen and Fuel Cells*, IEA 2005). Projected CCS costs are expected to add $1-$3/GJ, depending on process and scale.

■ **Coal gasification** produces a gas mixture of H_2, CO, carbon dioxide (CO_2) and methane (CH_4). The CO can then be converted into CO_2 and additional H_2 through a water-gas shift reaction. In addition to H_2, the final product offers relatively pure CO_2, ready for pressurisation and storage (CCS). Final H_2 purification is needed for most applications. Although a mature process, coal gasification is currently more expensive than natural gas reforming because of the gasifier and the need for O_2 for the reaction process. Large-scale, integrated gasification combined cycles (IGCC) are considered an attractive option for centralised co-generation of electricity and H_2, with comparably low CCS costs. Assuming costs of $1-$1.5/GJ for coal and $35-$40/MWh for electricity, with 45% electrical efficiency, projected H_2 production cost with CCS would range between $7 and $10/GJ$H_2$ (IEA 2005). IGCC demonstration plants are operating today in several countries to produce electricity (no H_2). They have proved more expensive and less reliable than conventional coal power plants. Cheaper gasifiers and new processes to produce O_2 could make IGCC plants more economically attractive. H_2 is also produced as a by-product from catalytic reforming in refineries, or through off-gas reforming in petrochemical plants, also from ethylene crackers, from chlorine plants and from coke oven gas. ■ **Thermal water-splitting** occurs at very high temperatures exceeding 2,500°C, but thermo-chemical processes such as sulphur-iodine (S-I) or bromine–calcium (Br-Ca) cycles may reduce temperatures to below 1,000ºC. These processes require low-cost high-temperature heat from nuclear or solar sources, also corrosion-resistant materials. The S-I process is the most promising, with about 43% LHV efficiency and an operating temperature of 950ºC. Cost projections suggest a H_2 cost of $10-$20/GJ using nuclear heat from nuclear high-temperature gas reactors (HTGR), and a cost of $20-$30/GJ using heat from advanced, megawatt-scale concentrating solar power (CSP) systems. Both technologies are unlikely to be commercial before 2030. ■ **H_2 from Biomass** is the only direct way to produce H_2 from renewable energy without major technology breakthroughs. Biomass can be converted into H_2 via various processes (pyrolysis, gasification, anaerobic digestion etc.). While R&D focuses on gasification, synergies with other fuel production processes (biofuels) could open the way to other options and accelerate market uptake. But H_2 production from biomass would compete with biofuels and CHP production. In general, as basic feedstock availability is limited, production from biomass will not benefit from large economies of scale. Costs are expected to be high compared with coal gasification or gas reforming. ■ **Photo-electrolysis** produces H_2 using sunlight to illuminate a water-immersed semiconductor that converts the light into chemical energy to split water into H_2 and O_2. This method promises lower capital costs than combined photovoltaic-electrolysis systems and it holds considerable potential for technology breakthroughs. Test-scale devices have shown solar-to-H_2 conversion efficiencies of up to 16% (IEA, 2005). But cost estimates are premature. ■ **Biological processes** derive H_2 from organic matter using micro-algal photo-synthesis and cyanobacteria. These processes require genetic engineering to achieve significant levels of H_2 production. Much research is still needed to demonstrate feasibility. ■ **Projected H_2 production costs** in Table 1 reflect a range of different technologies, economies of scale and energy prices.

DISTRIBUTION – ■ **Pipelines** are considered the only option to move large amounts of H_2. They have been used to transport H_2 for more than 70 years. Several thousand kms of H_2 pipelines are currently in operation world wide. The energy required to pump H_2 through pipelines is some 4.5 times higher than for natural gas per unit of delivered energy. As a consequence, long distances H_2 transportation for energy use may not be economically competitive. Transportation costs to deliver gaseous H_2 to refueling stations are in the range of \$1-\$2/GJ, assuming that H_2 compression to refueling pressure is included in the cost of the refueling station. ■ **Liquid H_2** transport by truck, rail or ship is more expensive than gas piping. In current plants, the electricity required for H_2 liquefaction at -253°C is about 35-43 MJ_{el}/kgH_2, with potential for future reduction to 25 MJ_{el}/kg. The cost of liquefaction in large systems is about \$7-\$9/GJ, 75% of which comes from the cost of electricity. Transportation of liquid H_2 by ship over long distances is also more expensive than for natural gas (LNG) since very low-temperature cryogenic technology is needed. Fast ships are required to reduce boil-off losses (0.2%-0.4% of liquid H_2 per day, which could be recovered, however, and used to fuel the ship). ■ **Refueling Stations** – Some 140 H_2 refueling stations are in operation world wide (90 under construction) to fuel some 400 FCV and 100 buses used in demonstration projects. Most stations deliver gaseous H_2 at 350 bar. H_2 is either produced on-site from electrolysis or steam reforming, or received from centralised plants. Costs of refueling stations are estimated between \$3/GJH_2 and \$10/GJ with centralised H_2 production and on-site production, respectively. These costs include investment and H_2 compression. Transportation, distribution and refueling stations may add some \$5-\$12/GJ to H_2 production costs.

STORAGE IN FCV – On-board H_2 storage for fuel cell vehicles (FCV) is challenging and may have significant impact on H_2 distribution infrastructure and standards (e.g. operating pressure). The target is to store 4-5 kg of H_2 (sufficient for a drive range of 400-500 km) while minimising volume, weight, storage energy, cost, and refueling time, and providing prompt H_2 release on demand. Storage requires energy-intensive compression at high pressure (350-700 bar) or liquefaction at -253°C. Electrical energy required for compression or liquefaction represents, respectively, some 12% or 30% of the H_2 energy content (LHV). Current commercial options do not fully meet requirements for compactness, drive-range, and cost. Liquid or gaseous storage at 700 bar both require more space than gasoline with equivalent energy content. The tank costs more than \$3,000-4,000 per vehicle. H_2 storage in solid materials may offer decisive advantages, but this is still under development, with a number of materials under investigation. On-board reforming to produce H_2 from fossil fuels has also proved challenging and expensive.

INFRASTRUCTURE - Estimates of H_2 infrastructure investment are complicated by significant uncertainty. The cost of H_2 supply infrastructure for road transport is estimated to be in the order of several hundred billion dollars. Assuming large-scale, centralised H_2 production, the cost of worldwide pipeline-based distribution systems for road transport could range from \$0.1 to \$1.0 trillion. The *incremental* investment in refueling stations would be somewhere between \$0.2 for centralised H_2 production and \$0.7 trillion for decentralised production. A full H_2 economy (i.e., widespread use of H_2 in transport and stationary sectors) would require global pipeline investment in the order of \$ 2.5 trillion, the bulk of which would be to finance supplying commercial and residential customers. Assuming early retirement or partial replacement of existing natural gas pipelines, a significant part of this cost would be *incremental*. The level of investment needed for H_2 infrastructure is not insurmountable when compared with the \$20-trillion investment in energy supply systems that is estimated to be needed if growth in energy demand up till 2030 is to be met (IEA *World Energy Outlook* 2006).

POTENTIAL & BARRIERS - According to *Prospects for Hydrogen and Fuel Cells* (IEA, Dec. 2005) and *Energy Technology Perspectives* (IEA, June 2006), H_2 is likely to gain significant market share over the coming decades if the cost of H_2 production, distribution and end-use fall significantly, and if effective policies are put in place to increase energy efficiency, mitigate CO_2 emissions and improve energy security. H_2 production costs should be reduced by a factor of 3 to 10 (depending on technologies and processes) and fuel cell cost by a factor of 10 or more. At the same time, emission reduction incentives of \$25-\$50/tCO_2 (depending on fossil fuel price) would help to make H_2, fuel cells and other clean energy options more competitive economically. Under these assumptions, emissions growth over the coming decades could be reduced in proportions that would bring annual emissions in 2050 down to half those projected in a business-as-usual scenario. Use of H_2 for energy applications would grow during the years starting from 2020 to reach some 12.5 EJ per year (0.3 Gtoe) by 2050, concentrated mostly on the transport sector. Thanks to the high efficiency of FCVs, this relatively limited input of H_2 (2%-3% of projected total primary energy supply) could fuel some 30% of the global fleet of passenger cars (about 700 million cars). If H_2 for FCV is combined with H_2 used in other applications (refinery and chemicals industries), total H_2 use by 2050 would amount to some 22 EJ (almost four times today's annual use of H_2). Under less optimistic assumptions regarding technology and CO_2 reduction policies, H_2 is unlikely to gain significant market share as alternative fuel and technology options (biofuels, Fischer-Tropsch synfuels, hybrids, battery-electric vehicles, etc.) could play a more important role in future. In addition to costs and competition from other technologies, barriers to H_2 market uptake include the need for dedicated infrastructure. However, no single fuel or technology is likely to meet the expected fast-growing demand for clean transport fuels. Various options are therefore expected to play complementary roles in regionally diversified markets.

Table 1 - Typical Data and Figures for H_2 Production & Distribution Technologies

Data Confidence – Industrial H_2 production is based on well known technologies, but new processes with higher efficiency, lower costs and eventually CCS are needed to produce H_2 for energy use. Typical figures for these technologies are more uncertain. H_2 costs are highly sensitive to coal, gas, biomass and electricity prices.

Current H_2 Annual Production: 65 million tonnes per year, equivalent to 8EJ (less than 2% of world total primary energy supply); 48% from natural gas, 30% refinery-gas/chemicals, 18% coal, 4% electrolysis

Efficiency of H_2 production from electrolysis (incl. auxiliaries, no compression)

Technology	Alkaline large-scale	Alkaline high-pressure	Advanced Alkaline	PEM	SOFC
Status	Commercial	Commercial	Precommercial	Precommercial	Prototype
T (°C) P (bar)	70-90 atm. to 25	70-90 up to 690	80-140 up to 120	80-150 up to 400	900-1000 up to 30
kWh/kgH_2	48-60	56-60	42-48	40-60	28-39

Efficiency of H_2 production from natural gas reforming (figures in brackets do not include compression)

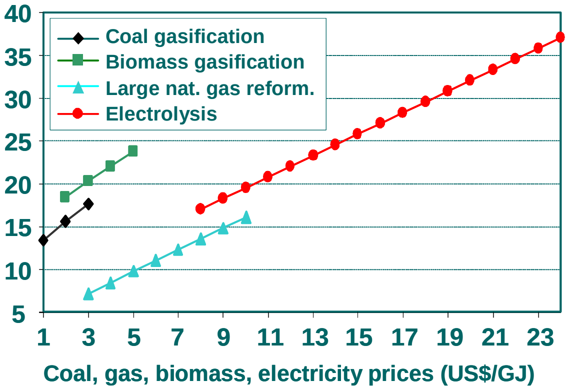
Technology	Steam reforming, large-scale 50 PJH_2/yr, 80 bar		Steam reforming small-scale 0.02 PJH_2/yr, 340 bar		Partial Oxidation	Auto-thermal Reforming
Status	Commercial no CCS	Future with CCS	Commercial no CCS	Future no CCS	Commerc. no CCS	Precommerc. no CCS
Effic. %, LHV	72-77 (76-80)	61-70 (62-78)	47 -55 (60-65)	60-65 (70-75)	66-76	66-73

Efficiency of H_2 production from coal gasification w/out electricity cogeneration (IGCC) - H_2 at 75 bar

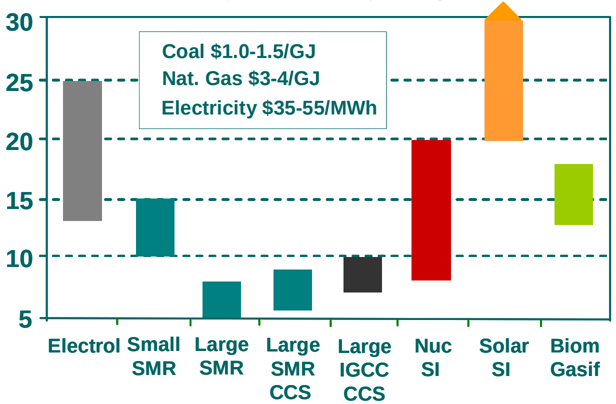
Technology	Current Gasification		O_2-blown Gasification		Adv.CO_2 Membr.Sep	Cogeneration		Cogeneration Membr. Sep.
Effic. %,	no CCS	CCS	no CCS	CCS	CCS	no CCS	CCS	CCS
LHV	57	51	67	62	64	83	70	77

Current and Projected H_2 Production Costs

Current H_2 production cost (US$/GJ)
Sensitivity to energy price



Projected H_2 production cost 2020-2030 (US$/GJ)
Sensitivity to technologies & processes



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