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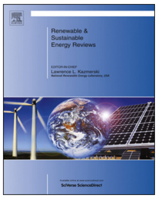

Automotive hydrogen fuelling stations: An international review

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ABSTRACT

Hydrogen produced from low-emission primary energy sources, particularly renewable energy, is a potential alternative transport fuel to gasoline and diesel that can contribute to reducing greenhouse gas emissions and improving global energy security. Hydrogen fuelling stations are one of the most important parts of the distribution infrastructure required to support the operation of hydrogen fuel cell electric vehicles and hydrogen internal combustion engine vehicles. If there is to be substantial market penetration of hydrogen vehicles in the transport sector, the introduction of commercial hydrogen vehicles and the network of fuelling stations to supply them with hydrogen must take place simultaneously. The present paper thus reviews the current state of the art and deployment of hydrogen fuelling stations. It is found that by 2013, there were 224 working hydrogen stations distributed over 28 countries. Some 43% of these stations were located in North and South America, 34% in Europe, 23% in Asia, and none in Australia. The state of the art in the range of hydrogen production processes is briefly reviewed. The importance of producing hydrogen using renewable energy sources is emphasised for a transition to hydrogen fuel cell vehicles to contribute to greenhouse gas emission reduction targets. 2.3–5.8/H_2kg for SMR A classification of hydrogen refuelling stations is introduced, based on the primary energy source used to produce the hydrogen, the production process, and whether the hydrogen is made on site or delivered to the site. The current state of deployment of hydrogen fuelling stations in each major region of the world is then reviewed in detail. The costs of producing hydrogen vary from $1.8 to 2.9/$H_2$ kg for Coal gasification, 2.3–5.8/H_2 kg for SMR, $6–7.4/$H_2$ kg for wind power and $6.3–25.4/$H_2$ kg depending on the cost of the PV system. The lowest cost of hydrogen is nearing competitiveness with petroleum fuels. Finally conclusions are drawn about the progress to date in establishing this crucial component of the infrastructure to enable hydrogen-powered vehicles to become a commercial reality.

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1. Introduction

The increase in energy demand in all sectors, the growth of the world's population, and the declining availability of low-cost fossil fuel sources are some of the most important issues the world faces in the 21st century. Fossil fuels such as oil, natural gas and coal are rapidly being depleted and polluting our environment, and they cannot be considered permanent and sustainable solutions to global energy requirements [1]. Consequently, any shortage of these types of energy sources could lead to fluctuations in oil prices and threaten global energy security and the world's economy [2]. As fossil fuels usage increases worldwide, local air quality falls and greenhouse gas (GHG) emissions increase. 33% of emissions in the USA are emitted by transportation (road, air, marine, and other), with just over three quarters of this amount coming from road transport; a further 41% are emitted by power stations, 16% from industry and agriculture, and 10% from other sources [3]. The latter are clearly leading to an increased world's mean surface temperature [4]. Marcinkoski [5] noted that some studies have estimated the cost of transportation-related emissions on public health to be between $40 billion and $60 billion every year.

For these reasons there is considerable interest in using hydrogen produced from low-emission primary energy sources, particularly renewable energy, as an alternative transport fuel to gasoline and diesel, and as an energy store to ensure reliable and continuous supply from intermittent and variable renewable energy sources. A growing number of studies see hydrogen as having a crucial role to play in a global sustainable energy strategy that on the one hand effectively reduces the threat of climate change and on the other provides a zero-emission fuel for transport to allow a gradual transition away from depleting gasoline resources.

For example, Dougherty and Kartha [4] investigated the transition to hydrogen energy in the United States of America (USA) for light- and heavy-duty vehicles, marine vessels and trains as a central plank of a sustainable energy strategy. The study found that hydrogen fuel cell electric vehicles (FCEVs), in conjunction with electric and other low-emission vehicles, could reduce GHG pollution by 80% in 2100 compared with that of 1990. Further, it would enable the USA to remove almost all controllable air pollution in urban areas and become essentially independent of gasoline fuel by the 2100s. IPCC (2011) – Summarise from Andrews and Shabani [6]. Balta-Ozkan and Baldwin [7] studied the role of a hydrogen economy and showed how it could meet the United Kingdom (UK) government's climate and energy policy goal to reduce 80% of national GHG emissions by 2050.

Andrews and Shabani [8] proposed six principles to guide the use of hydrogen in sustainable energy strategies globally and nationally and contribute to the transition to a hydrogen economy, and recently reviewed the role being projected for hydrogen currently [8].

Although hydrogen is not a primary energy source, it can, like electricity, serve as an energy carrier, and thus can replace fossil fuels in a wide range of applications [9]. Hydrogen can release energy through several different methods: direct combustion, catalytic combustion, steam production and fuel cell operations [10]. Among these methods, the fuel cell is generally the most efficient and cleanest technology for releasing energy from hydrogen [11].

In a fuel cell, hydrogen and oxygen are combined in a catalysed electrochemical reaction to produce an electrical current, water and heat. This process can achieve efficiencies that are two to three times those of internal combustion engines [11], while being quiet and pollution free. Further, developing hydrogen technology for producing, storing, distributing and using hydrogen energy can create many new jobs, as well as contribute to GHG reduction and assist in securing energy supplies, nationally and globally. Kohler and Wietschel [12] noted that 'results from the ASTRA model (Infrastructure investment for a transition to hydrogen automobiles) show that a transition to hydrogen transport fuels would lead to an increase in GDP, employment and investment'. According to McDowall and Eames [13], a transition to a hydrogen future would ameliorate carbon dioxide emissions, and FCEVs, in particular, can contribute significantly to the reduction of carbon emissions from the transport sector in the long term.

The most concern in using hydrogen is about safety issues. It is important to note, however, that exactly the same situation existed in the early years of using gasoline and diesel [14]. Hydrogen gas is nontoxic, environmentally safe, and has low radiation level, which reduce the risk of a secondary fire [15]. But special care must be taken since hydrogen burns with a colourless flame that may not be visible. Hydrogen has a faster laminar burning velocity (2.37 m/s), and a lower ignition energy (0.02 mJ) than gasoline (0.24 mJ) or methane (0.29 mJ) [10]. The explosion limits by volume for hydrogen in air of 18.3–59% are much higher than those for gasoline (1.1–3.3%) and natural gas (5.7–14%) [14]. The self-ignition temperature of hydrogen (585 °C) is significantly higher than for gasoline (228–501 °C) and natural gas (540 °C) [10]. It is almost impossible to make hydrogen explode in an open area due to its high volatility [16]. Since hydrogen is 14 times lighter than air, it rises at 20 m/s if gas is released [14]. Hydrogen is thus usually safer than other fuels in the event of leaks [17]. Cold burns and increased duration of leakage are a concern about liquid hydrogen, although hydrogen disperses in air much faster than gasoline [15].

Hydrogen is as safe as other fuels if appropriate standards and safe working practices are followed [18]. When stored at high pressures, the usual regulations and standards for pressurised gas vessels and usage must be implemented, and detection systems need to be employed to avoid any accident or components failure due to hydrogen attack (HA) or hydrogen embrittlement (HE) [10,17]. All components used in hydrogen fuelling stations must be certified by the appropriate safety authority. The California Energy Commission has identified 153 failure modes at hydrogen delivery stations (using liquid hydrogen and/or compressed hydrogen stations), and at on-site hydrogen production stations (using SMR and electrolysis hydrogen production) [17].

Stations with liquid hydrogen delivery have the most serious potential failures due to factors such as collisions, overfilling tanks, and relief valve venting [17]. For stations with electrolysers there are two low-potential failure modes and one medium failure mode [17]. The low failure modes are related to the electrolyser leak (oxygen, hydrogen, or KOH) and high voltages electrocution hazard. The medium failure is related to the dryer failure, which causes moisture to go into downstream components. Station with SMR has one medium-frequency rating failure, which is condensate separator failure that can cause fire or explosion [17]. Other SMR station failures are rated low frequency. Tube trailers have medium failure modes, such as dispenser cascade control failure, as well as hydrogen leaks due to trailer impact in accidents. Other failure modes with lower probability and less consequences have not been mentioned here.

Automotive companies have done a great deal of research on and have produced many types of successful fuel cell vehicle. Some of these companies, like Daimler, Ford and Nissan, have entered into agreements to develop and commercialise zero-emission vehicles based on hydrogen fuel cell vehicles [19]. Hyundai [20] announced its plans to produce 10,000 hydrogen fuel cell vehicles annually beyond 2015. Honda has built a production line for FCEVs, as has Toyota's first Concept FCV-R, which is expected to be ready for sale in the USA from 2015 [21]. Thirteen Japanese companies in addition to automotive companies are intending to support and supply hydrogen fuel for FCEVs under the direction of JX Nippon Oil [22,23].

Hydrogen fuelling stations are one of the most important parts of the distribution infrastructure required to support the operation of hydrogen-powered vehicles, both FCEVs and hydrogen internal combustion engine (HICE) vehicles. Without a hydrogen refuelling network, hydrogen vehicles cannot operate, and their commercial deployment will be very limited. Without a significant fleet of operational hydrogen fuel cell vehicles, it is not viable to invest in setting up a network of hydrogen fuelling stations. Hence if there is to be substantial market penetration of hydrogen vehicles in the transport sector, to meet greenhouse gas reduction targets and enhance energy security, the introduction of commercial hydrogen vehicles and the network of fuelling stations to supply them with hydrogen must take place simultaneously.

Hence the present paper reviews the current state of the art and deployment of hydrogen fuelling stations around the world. First the state of the art in the range of processes available to produce hydrogen is reviewed (Section 2). A classification of hydrogen refuelling stations is introduced in Section 3, based on the primary energy source used to produce the hydrogen, the production process, and whether the hydrogen is made on site or delivered to the site. In Section 4, the current state of deployment of hydrogen fuelling stations in each major region of the world – north and South America, Europe, and Asia – is reviewed in detail. Finally in Section 5, conclusions are drawn about progress to date in establishing this crucial component of the infrastructure to enable hydrogen-powered vehicle to become a commercial reality. In particular, the crucial question as to whether the current and planned hydrogen production, distribution and refuelling infrastructure can adequately support the commercial roll-out of hydrogen fuel cell vehicles over the coming few years is addressed.

2. Hydrogen production processes

2.1. Hydrogen production techniques

Hydrogen gas can be manufactured from different sources and in different ways. Hydrogen molecules are very light, which makes it very difficult for our planet's gravitational force to retain hydrogen gas in its atmosphere. Hence hydrogen is only available on the Earth in the form of compounds with other elements, such as water, hydrocarbons, hydrides of diverse kinds, and in a wide variety of organic materials. Hydrogen for use as a fuel must therefore be produced and manufactured from other hydrogen-containing materials such as fossil fuels, water, biomass or other biological sources. For over 100 years, hydrogen has been produced and used for industrial purposes. About 90% (45 billion kg) of hydrogen production currently comes from fossil fuel sources [24,25].

The main methods for producing hydrogen are presented in Fig. 1. Hydrogen can be produced directly from fossil fuels by the following processes by steam methane reforming (SMR), thermo cracking (TC), partial oxidation (POX), and coal gasification (CG). The main processes for producing hydrogen from biomass are biochemical and thermochemical (via gasification). Hydrogen can also be produced by dissociating water by electrolysis (HE), photoelectrolysis (PHE) or photolysis (also called photoelectrochemical or photocatalytic water splitting), water thermolysis (WT) (also called thermochemical water splitting), and photobiological processes.

All these processes require inputs of energy. In the case of conventional electrolysis, for example, the electrical energy input can be electricity generated by fossil fuel, nuclear or renewable energy power stations. The main forms of energy input (chemical, thermal, electricity, or solar radiation) required by each of the principal processes for producing hydrogen are shown in Fig. 1, along with the primary energy options for supplying this input (fossil fuels, nuclear or renewable energy of various kinds).

Greenhouse gas emission and other environmental impacts of hydrogen production processes depend crucially on the primary

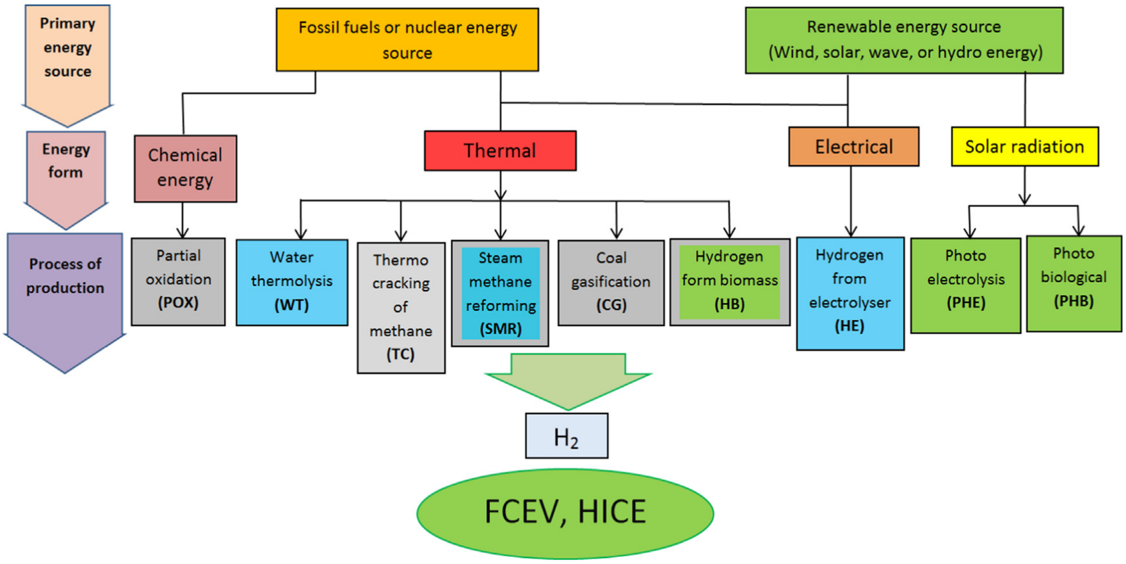


Fig. 1. Classification of hydrogen production methods.

energy source used to supply the process energy, as well as the raw material input, irrespective of whether water, biomass or fossil fuel. Crucially important to note here is that hydrogen is a zero greenhouse gas emission fuel only if it is produced entirely using renewable energy sources or nuclear power for process energy [25–28].

Fortunately, however, recent studies have shown that it is technically economically feasible to provide all the primary energy required by a global sustainable energy economy through to 2030 and beyond, including production of hydrogen to meet a substantial portion of demand in the transport sector. Jacobson and Delucchi [29,30] project that a shift to renewable energy sources to replace all fossil fuel and wood combustion by 2030, together with a shift to electricity and hydrogen as energy carriers, and strong energy efficiency measures in all sectors, could reduce the global demand to 8% less than in 2008. They show how this demand could be met entirely from renewable sources such as wind, wave, hydro, geothermal, photovoltaic and solar thermal power technologies.

Partial oxidation (POX) is a chemical reaction used to produced hydrogen from natural gas (mainly methane) or other hydrocarbons (such as crude oil and coal) by combustion with reduced amounts of oxygen at 1200–1400 °C [27] and 700–1000 °C when using catalysts [28].

The POX process produces hydrogen at a faster ratio than SMR, but less hydrogen from the same amount of raw material [9], so that its thermal efficiency is only 71–88.5% (at HHV) [28].

Water thermolysis occurs when water is heated to over 1927 °C. But dissociation temperature can be reduced to around 1000 °C using catalysts such as sulphur-iodine or bromine-calcium [31]. The thermolysis process does not emit CO_2 into the atmosphere when a renewable energy is used to supply the required heat [25]. The challenge of this process is not to make an explosive mixture with a high risk of combustion [28] and to avoid the recombination of hydrogen and oxygen back to water [26].

Thermo-cracking (TC) derives hydrogen from natural gas at 1600 °C using a plasma burner to decompose methane into hydrogen and carbon [10]. The average energy efficiency of this method is around 45%, which is much lower than the SMR process (85–90%) [10,32]. However, the methane-to-hydrogen conversion rate can reach 98% [33].

SMR is currently the most widely used hydrogen production method [28]. It involves two reactions: first the production of some hydrogen plus carbon monoxide by reacting methane with steam (an endothermic processes taking place at 700 to 1000 °C), and second, the production of more hydrogen plus carbon dioxide as the carbon monoxide reacts with steam (the shift reaction at 200–500 °C and 3–25 bar), which is exothermic [10,25,34]. The energy process efficiency of SMR varies from 85% (at HHV) to 90% when some of the input heat is recovered. However, the efficiency can be much lower, at only 47–55%, for small-scale commercial reforming stations [3,27,31].

Coal gasification (CG) is the oldest chemical method to produce hydrogen, with coal and water heated up to 900 °C, producing a mixture of steam and other gases that is passed over a catalyst, usually made of nickel, to give hydrogen and carbon dioxide [25]. The working energy efficiency can reach 67% at HHV [31], but 11 kg of CO_2 is released into the atmosphere for every 1 kg of hydrogen produced, based on the stoichiometry of the overall reaction.

Biomass contains about 6–6.5 mass% of hydrogen [25], which can be released from the biomass by two main processes: thermochemical gasification and biochemical production processes at 600 °C (Bio-oil) [25,35]. The energy efficiency of these processes varies from 41 to 59% [28] (based on HHV). Biochemical production process has three advantages over biomass gasification: bio-oil is easy to handle, can readily be stored, and can be a source for some chemicals [36]. Nevertheless biomass to hydrogen conversion process is not yet practically proven for high volume production (more than 155H_2 tonnes/day) [9,25].

A water electrolyser can use any electrical source to split water into hydrogen and oxygen (1:8 by weight and 2:1by volume) with 55–75% energy efficiency for commercial electrolysers [28,31,37,38] without emitting any GHG [31].

The hydrogen purity from alkaline electrolyser can reach 99.8%, with an energy efficiency of around 70–80% (HHV) [39–41] and 99,999% hydrogen purity for proton exchange membrane (PEM) electrolyser with up to 89% energy efficiency [31,38].

Photolysis is the direct production of hydrogen by water splitting in a single photoelectrochemical cell (PEC), using solar radiation as the input. The highest efficiency of photolysis systems yet reported is 12.3% [42], but this is only in an experimental unit producing a very small amount of hydrogen [43–45].

Photolysis is still under active research and there is no estimated cost for commercial hydrogen production by this method currently [26,28].

Photobiological hydrogen production process uses certain types of bacteria, called cyanobacteria or blue-green algae, to evolve hydrogen by a process that has some similarities to photosynthesis [25,32,46]. Although theoretically the efficiency of hydrogen production by these processes can reach 25%, only very low efficiencies have been achieved to date. Moreover, a mixture of hydrogen and oxygen is produced, from which the hydrogen must be separated [46].

At present the algae employed can only withstand very low levels of solar radiation (up to around 0.03 suns), so a lot of further work is needed to make this a practical process for producing hydrogen [32].

Anaerobic Microbial Communities or dark fermentation is another type of biological hydrogen production process, which uses organic waste as the substrate. Dark fermentation can produce 12 mol of H_2 from 1 mol of glucose and emit 5.5 kg CO_2/ kgH_2. However, the best practically dark fermentation produces only 2.3 mol of H_2 for every mol of glucose, which is 20% of the theoretical process [47]. Dark fermentation is still under research and development and the main challenge of this process is related to pH, treatment temperature, and substrate types, which can result in eliminating hydrogen consumption bacteria and improving hydrogen production bacteria to maximum hydrogen production [32,47].

2.2. *Comparison of hydrogen production methods*

Table 1 presents an overview of the technical and economic information on the different hydrogen production methods outlined in the previous section.

Production processes 1–5 in the table use hydrocarbons as a raw material, so that all of these emit GH gases. Theoretically coal gasification process has the highest GH gas emissions into atmosphere (11 kg of CO_2 for every kg of H_2), while SMR is the lowest at 7.05 kg of CO_2 per kg H_2. The biomass hydrogen production process emits about 5.43 kg CO_2/kg H_2, although from a complete cycle perspective much of this emission is offset by carbon dioxide absorption from the atmosphere during the growth of the biomass feedstock. Methane partial oxidation has the lowest CO_2 production as by-product from the process itself, emitting less than 3 kg CO_2/kg H_2 without taking into consideration GH emitting from the energy source.

The methane thermal cracking process does not emit GH gases by itself, and can be zero emission if a totally clean energy source is used. However, it produces less hydrogen per unit mass of methane input than SMR.

Table 1
Technical and economic information of the different hydrogen production methods.

		Resource inputs	Mass per cent of hydrogen in raw material	Primary energy form	Temperature (°C)	Hydrogen purity	GH impact (kg CO_2 per kg hydrogen)a	Energy efficiencies b	Production cost ($/kg) c
1	Steam methane reforming	steam + CH4	25% [25]	Natural gas (thermal)	700–1000 [25]	70–75% [27]	7.05 [27]	60–85% [10]	2.3–5.8 [49] [27]
2	Thermal cracking of methane	CH4	25% [25]	thermal	1600 [10] depending catalyst	Pure hydrogen [10]	Depends on heat energy source [10]d	45% [10] 16% for solar energy [33]	3.1–4.1 [50]
3	Biomass production	Biomass (thermochemical or biochemical)	6–6.5% [25] 4%[10] (pyrolysis)	Thermal	600° [35]	-	5.43 [51]e	$>30\%$ [25] 41–59% [28] 45–50% [52]	2.3–3.3 [27,53] 8 [54]f
4	Partial oxidation (CH_4)	hydrocarbons (CH_4)	25% [25]	Chemical energy (Burning)	1200–1500 [27] [25]	-	$\leq$ 3 e	71–88.5%[28]	-
5	Coal gasification	Coal + steam	13% (R&D) [55]	thermal	900 [25]	90% [48]	11 [56]e	60% [52] 67% [31]	1.8–2.9 [27,57]
6	Water electrolyser with grid electricity	Water	11.2% [25]	Electrical	80–150 [31,40,58]	99.8–99.999% [25]	Depends on GH intensity of grid power	25–38% [27,31,32]	3.6–5.1 [59]g
	Water electrolyser with wind power	Water	11.2% [25]	Electrical	80–150 [31,40,58]	99.8–99.999% [25]	0	13- $>20\%$ [31,60] h	6–7.4 [61] [27]
	Water electrolyser with PV	water	11.2% [25]	Solar radiation	80–150 [31,40,58]	99.8–99.999 [25]	0	10% [27] 16%,[24] j 20% [32]	6.3–25.4 [61] i
7	Thermolysis	water	R&D	thermal	1927–2500 [25,31] <1000 [31]	–	Depends on heat energy source d	$\approx 50\%$ [31,52]	R&D
8	Photolysis (PHE)	water	early R&D Short lifetime	Solar radiation	Low temp	$>99\%$	0	7.8 [25] to $<12.3\%$ [10,24,42,52]	R&D
9	Photo biological	water	early R&D	Solar radiation	Low temp	$>99\%$	0	≈ 10 [25] $<1\%$ [52]	R&D k

a-Excludes emissions in constructing equipment.
b- Energy efficiency is defined here as the energy content of the hydrogen produced (using HHV) divided by the energy content of the raw material (HHV) plus any additional energy inputs required during the production process.
c- The price has been adjusted to be equivalent with $US at 2014 by using the US inflation calculator (2014).
d- The amount of GH impact produced by thermal carking depends on heat energy source, but when a solar concentrator is used, the GH impact will be zero. Also it is difficult to find a suitable catalyst; however, if hydrogen is used for heat, GHG can be eliminated [10].
e- Theoretical based on stoichiometry in chemical equation.
f- For 500 t of dry biomass ton per day (dtpd)
g- This is based on electricity cost of 0.039–0.057 $/kW. About 75% of hydrogen costs from electrolyses depend on the electrical processes [40].
h- That if estimating the electric efficiency is 45% for grid power and 24% for wind turbine [60].
i- Depending on the cost of the PV system
j-The theoretical efficiency of photo electrolysis believes that it can reach 35% [24].
k- Expect to cover around 90% of the cost involved in H_2 production due to the use of contents after that for animal feed.

Processes 6 and 7 use water as a raw material, so that the environment impact of hydrogen production depends solely on that of the energy sources employed. Thus if RE sources are used, there will be no GH emissions. Methods 8 and 9 do not emit GH into the atmosphere, although these processes are still at the laboratory phase of development.

Table 2 also shows the overall energy efficiency for every production method. In general, this efficiency for hydrogen from fossil fuels varies from 45% for methane thermal cracking to 85% for SMR and methane thermal cracking with a plasma burner. Biomass efficiency starts from just over 30% and can reach 50%, which can therefore be a competitive rate with many other production methods.

The maximum achieved efficiency of photolysis is currently 12.3% and with most actually operating experimental systems much lower still at less than 8%. Efficiencies for photo-biological processes of up to 10% have been claimed, while water thermolysis can achieve up to 50% efficiency, using concentrated solar radiation or nuclear thermal energy. All these methods are still under study and development and are not yet for use in commercial production. Thermal cracking of methane is also still under development due to its high temperature and the difficulty of finding a suitable catalyst.

Table 2
Hydrogen fuelling station numbers around the world (main sources: [64,67,68,73–76]).

Station type	Continents					
	North America	South America	Europe	Asia	Australia	Total
RE energy	12	0	15	1	0	28
Partial RE energy	2	0	0	0	0	2
On-site electrolyser (grid power)	23	2	7	5	0	37
Reforming	12	0	9	21	0	42
Delivery	22	0	22	15	0	59
Not identified	23	0	24	9	0	56
Total	94	2	77	51	0	224

Reported production costs (in US$2014/kg of hydrogen) are provided in the final column of the table. These unit costs depend on a wide range of factors, including the raw material inputs, transport costs, the processing energy required, the energy efficiency of the process, plant size, the annual utilisation of the plant, and geographic location [9]. Hence the figures given here are indicative only, and are presented as ranges to reflect the different conditions that may apply, as well as technological uncertainties.

SMR using natural gas and steam as raw materials produces hydrogen at a unit cost between 2.3 and 5.75 US$/kg, with the local cost of the natural gas being a key variable here. Currently, SMR is the most cost-effective hydrogen production method; although this advantage could disappear if real natural gas prices increase. The production cost of methane thermal cracking of methane is around 3.1–4.1 US$/kg, and both SMR and methane partial oxidation cannot constitute as a truly sustainable solution for hydrogen production into the long-term, because they are not zero emission and as natural gas demand increases in the face of declining low-cost supply, real price increases are inevitable.

Coal gasification is the most competitive process to SMR with costs in the range started from 1.8 to 2.9 US$/kg, although the amount of CO_2 emitted is very high compared to all other production methods. Coal gasification can only be a zero emission hydrogen production method by capturing and sequestering the emitted [48].

Hydrogen production from biomass cost is estimated from 2.3 to 8 US$/kg, which is more than SMR and methane thermal cracking. In this process, hydrogen can be achieved in two different methods, thermochemical and biochemical. However, when there is no infrastructure for natural gas, producing hydrogen from biomass can be competitive and cheaper than SMR [25], but for large plants this process is not practical due to large production and feedstock limitations (155 t/day) [9].

Hydrogen produced by the electrolysis of water is the most common process used. The USA and Europe have on-site hydrogen stations to obtain hydrogen. Although, in this situation, energy consumption levels have produced the highest hydrogen production cost, it remains the cleanest process and has a wide range of system sizes, which makes it more flexible than other energy sources. Hydrogen from an electrolyser drawing on grid power is estimated to cost from 3.6 to 5.1 US$/kg with about 75% of the production costs coming from electricity. The cost increases when using renewable energy sources, 6–7.4 US$/kg for wind and 6.3–25.4 US$/kg for solar and without any GHG.

The last three processes – thermolysis, photolysis and photobiological – are still under research and development so no unit costs are given for these processes.

3. Classification of hydrogen fuelling stations

3.1. Basic types of station

There are two basic types of hydrogen fuelling station (hereafter simply called ‘hydrogen station’):

1. stations in which the hydrogen is made elsewhere and delivered to the station for local storage and dispensing to vehicles
2. stations in which hydrogen is made on site, and then stored there ready for transfer to in-vehicle hydrogen storage.

Some stations may be a combination of both types using delivered hydrogen to supplement on-site production as required.

Once the hydrogen is obtained, hydrogen stations use the same principles that ordinary gasoline stations use, such as storing hydrogen in a reservoir, transferring it to a dispenser, and then filling on-board hydrogen tanks as hydrogen-powered vehicles require refuelling. Hydrogen dispensers for high-pressure gas look like LPG or compressed natural gas dispensers and connect to vehicle tanks in a similar way (Figs. 2 and 3).

Fig. 2. Typical hydrogen fuelling station [62].

3.2. Type 1: stations with hydrogen delivery

In type 1 stations with hydrogen delivery, hydrogen is produced off-site at an industrial facility (often petrochemical) and delivered to the site using a pipeline, road or rail tanker, or ship (Fig. 4).

In general, a type 1 hydrogen station consists of six main elements, if the energy sources are not taken into consideration (Fig. 4) (CFCP, 2013):

1. A receiving port, used to receive compressed or liquid hydrogen from a tanker or pipeline.
2. A control system to manage all transfers and storage of hydrogen, including pneumatic valves, pumps, sensors, and oversee the safety of the overall.
3. Heat exchangers to heat the liquid hydrogen and change it to a gas before it is compressed, and a liquid/gas distribution system comprising valves, pipes, gauges and pressure relief devices.
4. The compressor or air booster to compress hydrogen typically to above 350 or 700 bar for storage at high pressure.
5. A liquid hydrogen reservoir (if delivery is as liquid hydrogen), low-pressure hydrogen storage tanks (after conversion of liquid to gas), and high-pressure hydrogen storage tanks.
6. Dispensers taking high-pressure hydrogen from storage tanks and filling the on-board high-pressure hydrogen tanks of hydrogen fuel cell electric vehicles (HFEV) usually through 350- or 700-bar nozzles.

A high-pressure electrically powered compressor plus a hydrogen pressure booster is used to pressurise the hydrogen up to 875 bar for storage in high-pressure tanks (typically 700 bar) [27]. To transfer and distribute hydrogen between components, suitably manufactured materials, pipes, valves and elements should be used to avoid any failure in the system that can be caused by direct contact with hydrogen [10]. Storing hydrogen at high pressure allows drivers of fuel cell vehicles to refuel their tanks in about the same time as for gasoline vehicles, that is, in three to five minutes. The process of refuelling vehicles with hydrogen is similar to filling a vehicle with compressed natural gas or propane and the sound is similar to that produced when blowing up a car tyre with compressed air.

Hydrogen is usually transported as a compressed gas or as liquid hydrogen to a type 1 hydrogen station. Compressed hydrogen gas transportation is preferred for covering short distances and can be done by truck, rail or short pipelines. For longer distances, hydrogen can be transported by road, rail or ship tanker as liquid hydrogen or compressed gaseous hydrogen. Pipeline delivery can be used for longer distances (100 km and more)[10].

Compressed hydrogen is conveyed at high pressure (current standard 170–200 bar) in containers that are resistant to hydrogen embrittlement. Equipment such as pipelines, reservoirs, cylinders and hydrogen storage should be certified as compatible for use with hydrogen by an authorised authority, such as in the USA the American Society of Mechanical Engineers (ASME) for stationary applications, or by the US Department of Transportation (DOT) for transport or delivery usages[27].

Hydrogen can be transported by sea over large distances as a liquid in tankers with cryogenic storages, although having many features in common with LNG tankers. In particular very high-grade insulation of tanks is required to maintain the very low temperatures needed to keep the hydrogen as a liquid (in the order of 20 K)[65]. In addition, there is an opportunity to use some of the hydrogen carried as fuel for a fuel-cell powered ship.

Kawasaki Heavy Industries Ltd (KHI), in Japan, aims to build the first distributed hydrogen energy ship to carry liquefied hydrogen as a demonstration by 2017. Carrying the liquefied hydrogen is expected to cost US $610 million [66]. Currently the company has two conceptual designs for 16,400 kg of hydrogen tanker, spherical tank and prismatic tank design (200,000 m^3). These are based on existing technologies for LNG tankers [65].

A cryogenic liquid hydrogen road trailer is an option for local distribution of hydrogen made at a central plant to hydrogen stations. At the hydrogen station, the liquid hydrogen is heated, by a small heat exchanger, to produce a gas before being fed to a compressor and stored at a high pressure, 35 or 70 mega pascal (called “H35” and “H70”).

Fig. 3. Hydrogen-fueling-station-at-california-state-university. [63].

3.3. *Type 2: stations with on-site hydrogen production*

In an on-site hydrogen production station, a number of production methods can be used to produce the hydrogen from locally available energy and feedstocks such as water, biomass, or fossil fuel.

With on-site hydrogen production (Fig. 5), hydrogen can be produced by using any of the hydrogen production methods depending on the energy source. Some of these methods use a renewable energy system (wind energy or solar energy) and others use a fossil fuel source. The two main methods of onsite hydrogen production are water electrolysis and steam methane reforming.

4. Hydrogen fuelling stations around the world

4.1. *Overview*

Most current hydrogen stations around the world have been built, managed and designed by universities, research centres, industry shareholders, governments or non-governmental organ. The design of every station is subject to the partners' goals with respect to what they want to study or achieve. The main goal of these stations is to contribute to a practical distribution network for supply of hydrogen station to FCEVs and hence contribute to their deployment [67,68].

Before widespread marketing and sale of FCEVs, hydrogen fuelling stations must be available sufficiently close to consumers’ homes and workplaces with sufficient capacity supply to fill up their vehicles. In the early-commercial phase, the California Fuel Cell Partnership Members (consisting of 36 members) planned a hydrogen station network of 68 stations in Santa Monica/ West Los Angeles, Torrance, Irvine and Newport Beach, and the San Francisco Bay Area, to serve 10,000–30,000 FCEVs [67]. Exactly the same situation existed in Europe under the The HyWays Project phase one and two that aim to sale 0.4–1.8 million FCEVs annually by 2020 [69]. In Asia, Japan aims to deploy 2 million FCEVs and construct about 1000 hydrogen fuelling stations by 2025 under Fuel Cell Commercialization Conference [70] in addition to the Korea roadmap, which planned to open 43 hydrogen fuelling stations and production 10,000 FCEVs annually beyond 2015 [71,72] (Fig. 6).

According to netinform [64], FuelCells2000 [68], CFCP [67], Matthey [73], [74], and [75] there were more than 224 hydrogen

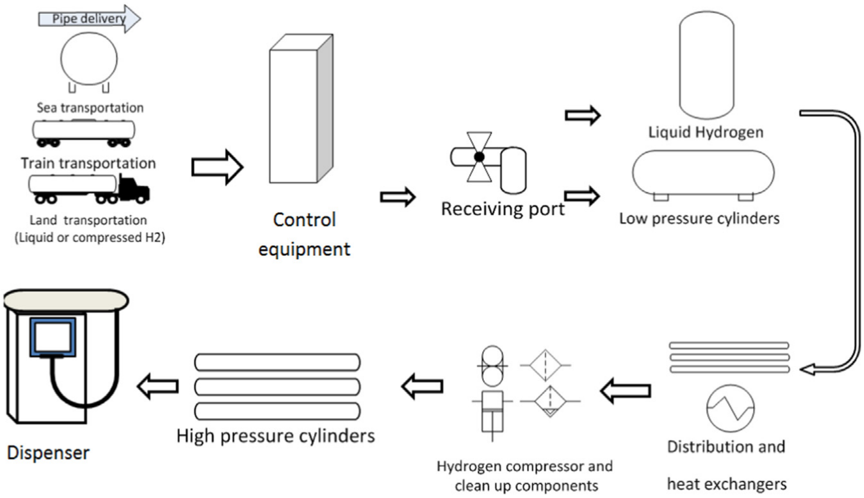


Fig. 4. Typical elements of a hydrogen fuelling station with hydrogen delivery.

stations in 28 countries around the world in 2013 (Figs. 6,7 and Table 2).

It can be seen from Table 2 that North America is the world's top continent for hydrogen station numbers, with 94 stations using all types of hydrogen production technique. These stations are spread across the USA with 81 stations, Canada with 13 stations, and Mexico with just one planned station. Europe has the second most hydrogen stations, with 77 stations spread across 17 countries, followed by Asia with 51 stations in nine countries.

There are only two stations in South America, and no stations in service in Australia currently; the only Australian hydrogen station was closed in 2007.

The Perth hydrogen fuelling station was set up specifically to support the Daimler Chrysler hydrogen fuel cell bus trial over the period August 2004 and ended in September 2007 [77]. The fuel cell buses used Ballard Xcellsis HY-205 fuel cells [77]. Over this time, this trial successfully demonstrated the operational reliability, public acceptance, and a greenhouse gas reduction of more than 50% of the fuel cell bus fleet [78]. This hydrogen fuelling station ceased to operate at the end of the bus trial, since there was no continued funding to keep the station and the fuel cell buses in operation. Currently there are no hydrogen stations operating in Australia.

Fig. 8 shows the distribution of current hydrogen stations by type around the world. On-site electrolyser with grid power is the most-used hydrogen production category in North America, followed by the hydrogen delivery technique. In Europe, hydrogen delivery techniques are the most common, followed by stations producing hydrogen on-site with renewable energy.

Generally, current stations are using various techniques in terms of hydrogen production, hydrogen compressing and hydrogen storing and dispensing pressure (350 or 700 bar). The daily hydrogen production rate and station storage capacity determine the number of FCEVs that can be served. Some of these stations use a renewable energy source such as solar or wind turbine, although most of them rely on grid energy sources but use hydrogen delivery techniques. Most hydrogen stations use PEM electrolysers to generate hydrogen and a diaphragm hydrogen compressor because of its high safety level, no contamination, and low leakage rate. Some other stations use piston compressors, and Linde uses ionic compression, which uses less electricity than other hydrogen compressor types in fuelling stations and requires less maintenance [68,79]. Linde ionic compressor consists of five stages of pistons compressor, moving hydraulically up and down. The ionic liquid is the top of the pistons which works as liquid pistons and compressed with hydrogen. At end of the process the hydrogen passes through a separator to separate the ionic liquid from the hydrogen and return it to the system [79].

The USA is the only country that has a partially renewable energy station; it was built, in 2010, and is managed by Honda R&D.

Hydrogen stations using delivery techniques are usually characterised by a relatively higher hydrogen storage capacity and they

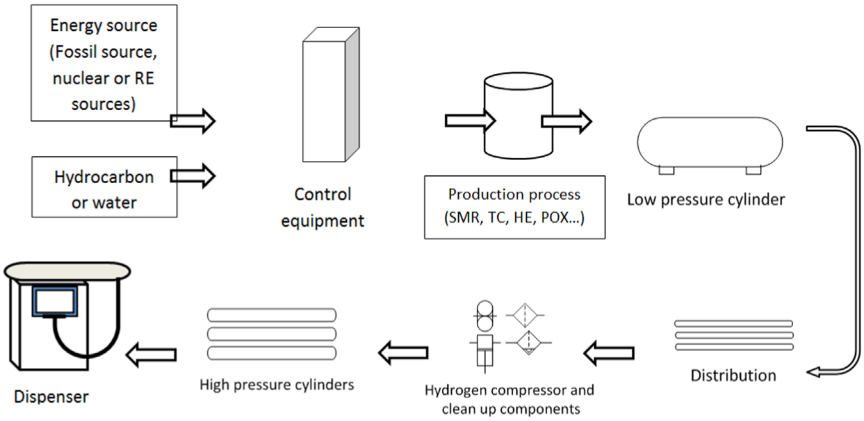


Fig. 5. Typical components of a hydrogen fuelling station with on-site hydrogen production.

Fig. 6. Hydrogen fuelling station worldwide [97].

can serve a higher number of FCEVs. Some of these stations are run by companies with on-site hydrogen production (SMR or water electrolysers) or they use renewable energy sources, which enables the study of hydrogen technology from different perspectives. Hydrogen delivery usually requires a pipeline or certified truck tankers to transfer hydrogen to the stations.

4.2. Hydrogen fuelling stations in North and South America

In 2003 President Bush announced that the USA would support R&D into hydrogen energy and that FCEVs would be the replacement for internal combustion engine vehicles using gasoline. He promised that the new FCEVs would have zero pollution and use hydrogen fuel instead of gasoline. He believed that this technology would make air cleaner and more healthy as the only by-product from FCEV is water.

In March 2012, Governor Jerry Brown (State of California) signed Executive Order B-16–2012', which guides state actions to support and simplify the rapid commercialisation of ZEVs (plug-in electric vehicles [PEVs] and FCEVs) and work on the three main stages [80]. First, society must be ready for plug-in and hydrogen vehicles and infrastructure in 2015. Second, California will have established sufficient infrastructure to support one million ZEVs in 2020. Third, more than 1.5 million ZEVs (BEVs, PHEVs and FCEVs) will be on the road and the market will expand in 2025, to move from the current pre-commercial phase of FCEV deployment (2012–2014) to the primary commercial phase (2015–2017). These stages are expected to contribute to describing the gaps and provide answers to how these complications can be bridged [67].

Greene and Leiby [82] cited that the Brian and Perez (2007) study shows three scenarios and phases for growing FCEV and hydrogen station distributions in the USA, over the period from 2012 to 2025. Their study aimed to distribute low-cost hydrogen, which fosters public acceptance and reduce government investment. The first phase, scheduled for 2012–2015, began by introducing the public to this technology. The second phase is concerned with geographical distribution, scheduled for 2016 to 2019. The third phase, from 2020 to 2025, aims for geographical growth [82].

Table 3 presents 73 stations in North and South America, which vary between delivery and on-site hydrogen production techniques. About 70% of these stations are using on-site hydrogen productions (small SMR or electrolyser); hence, more than 30% are using delivery techniques, which vary between road transport and pipelines. Most of these stations (43 stations) are in the USA and have on-site hydrogen production; 19 use hydrogen delivery.

Whistler's hydrogen fuelling station was opened in 2010, in British Columbia, Canada, and was claimed to be the largest FCEV hydrogen fuelling station in the world at that time, using the hydrogen delivery technique. Whistler's station can operate a fleet of 23 hydrogen fuel cell buses with a total of 28 buses. The station is capable of dispensing 1000 kg of hydrogen per day, which is provided by Air Liquid and stored in a cryogenic tank. This station is one of the 40 stations that have been installed by Air Liquids throughout the world [83].

AC Transit's Oakland Station in the USA (CA), which opened in 2006, represents the largest hydrogen station with on-site hydrogen production. The station has the ability to generate and store up to 150 kg of gaseous hydrogen, using an SMR of natural gas, enough to fuel three fuel cell electric buses. The station is equipped with 366 kg of gaseous hydrogen storage and two gaseous hydrogen dispensers, with 200 kg per day at about 350 bar (DOE 2014). The aim of this project is to demonstrate and gather data about hydrogen infrastructure and FCVs so that they can become an everyday reality [84](Figs. 9 and 10).

Fig. 7. Hydrogen fuelling stations in the USA and Europe [97].

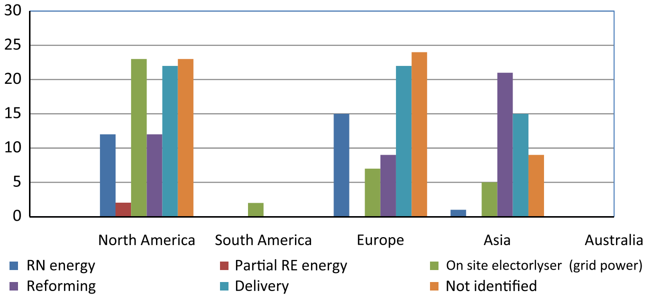


Fig. 8. Hydrogen fuelling stations by type around the world: [64,67,68,73,76].

Table 3
Hydrogen fuelling stations by type in North and South America (main sources: [64,67,68,73]).

Station type	Country					
	USA	Canada	Mexico	Brazil	Argentina	Total
On-site hydrogen production	43	6	0	1	1	51
Stations with hydrogen delivery	19	3	0	0	0	22
Total	62	9	0	1	1	73

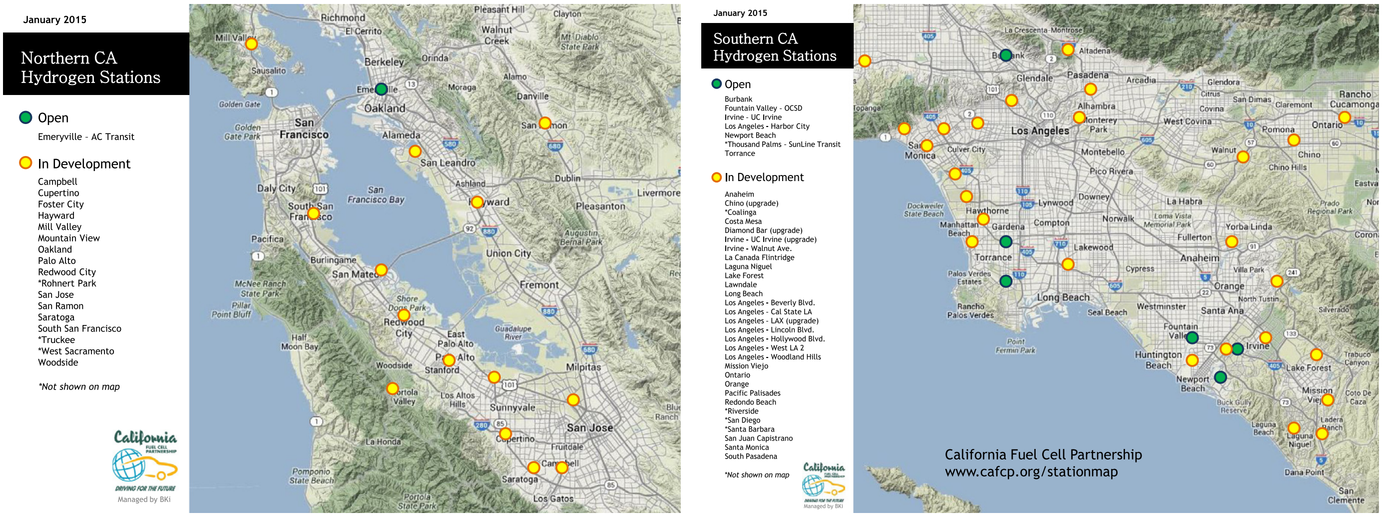


Fig. 9. The current hydrogen station network in the Greater Los Angeles and the San Francisco Bay Area [81].

Table 4 and Fig. 11 present only the hydrogen stations in North and South America according to their energy source and environmental effects (production types, taking out the unidentified stations). There are 11 zero emission and two partially renewable energy stations in the USA, and only one zero emission station in Canada. There are two on-site hydrogen production stations in South America, in Brazil and Argentina, which are classified as having environmental effects (on-site electrolyser using grid power).

AC Transit Emeryville Station is the second-largest hydrogen station in North America and has a dispensing capacity of 600 kg per day. Designed, constructed and operated by the Linde Group, this station uses partially renewable energy sources and is capable of operating 32 ZEVs, 20 FCVs passenger cars and 12 fuel cell buses per day, in the East Bay Area. The buses take 30 kg each, and the passenger vehicles take 6 kg each, using 350-bar and 700-bar fuel systems for passenger vehicles and 350 for buses [79].

This project seeks to demonstrate the commercial viability of hydrogen fuel cell technology for the public transport industry. This station uses two methods for obtaining hydrogen: 510 kW DC solar photovoltaic system to run a PEM electrolyser, and hydrogen delivery by Linde [68]. The renewable system generates 60 kg/day and Linde provides liquid hydrogen in a cryogenic tank [79]. Two methods are used to compress hydrogen in this station: piston compressor and ionic compressor.

The hydrogen fuelling station in Boulder, Colorado, is one of the many zero emission hydrogen fuelling stations in the USA. The station was constructed in 2009 and uses two renewable energy sources—wind and solar power—prepared with two types of electrolyser, to generate hydrogen from water (100-kW turbine) and wind (10-kW turbine). Alternating current (AC) power from the 10-kW wind turbine is converted to a direct current (DC) and then used by two HOGEN polymer electrolyte membrane electrolysers (40RE proton) and one alkaline electrolyser (Teledyne HMXT-100) to produce hydrogen [68].

The generated hydrogen is stored in 130-kg cascading storage tanks at 413 bar and used to fuel FCEVs and to generate electricity. It is also fed into the grid during peak demand time. The system uses a 350-bar pressure system to fuel four Toyota FCE passenger vehicles and shuttle bus; it takes from 20 to 30 min to fuel buses. The project is managed and operated by the NREL [64].

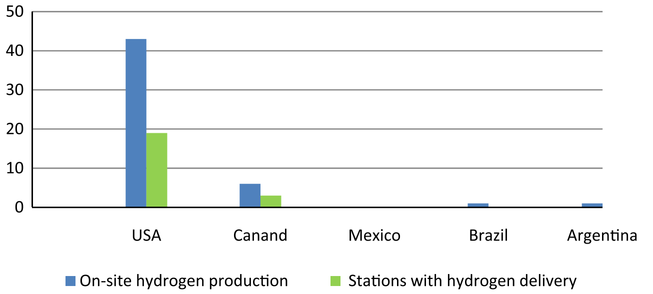


Fig. 10. Hydrogen fuelling stations in North and South America (delivery and on-site production). Main sources: [64,67,68,73].

Table 4
Relatively low GH emission hydrogen fuelling stations in North and South America (main sources: [64,67,68,73]).

Station type	Country					
	USA	Canada	Mexico	Brazil	Argentina	Total
RE energy	11	1	0	0	0	12
Low to medium GH emission	2	0	0	0	0	2
High GH emission	49	8	0	1	1	59
Total	62	9	0	1	1	73

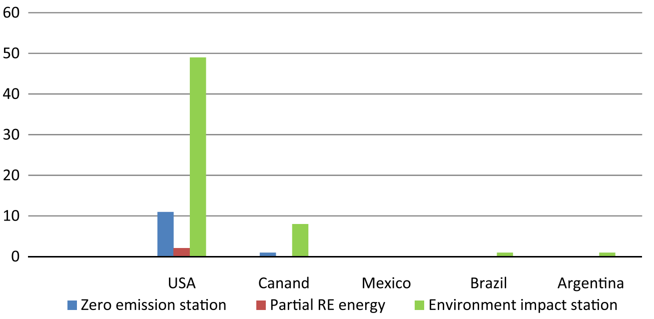


Fig. 11. Hydrogen fuelling stations in North and South America (production types). Main sources: [64,67,68,73].

4.3. Hydrogen fuelling stations in Europe

Europe's Annual Implementation Plan (AIP) for Fuel Cell and Hydrogen, 2013, is the result of a joint undertaking by major stakeholders and the European Commission (EC). It represents a set of important actions, and the long-term objectives of the Fuel Cell and Hydrogen Joint Undertaking [85]. These actions will be implemented on a yearly basis to encourage the rapid deployment of FCH technologies and achieve FCHJU's objectives. FCHJU's overall programme is divided into four main application areas [85]:

- Demonstrate FCEVs on a large scale and build up the required refuelling infrastructure for vehicles from 2015.
- Develop hydrogen production, storage and distribution.
- Support the development of commercially relevant technologies of stationary power generation and CHP.
- Encourage and support early-market FCH technology.

European Commission also founded HyWays project which “aims to develop a validated and well accepted roadmap for the introduction of hydrogen in the European energy system until 2030 and provides an outlook to 2050”. At first phase there were six countries (Germany, France, Greece, Italy, Norway, and the Netherlands) and the second phase the UK, Finland, Poland, and Spain have joined the projects (Fig. 12)

In addition to AIP and HyWays, an alliance of German companies (Fig. 13) set itself a plan of establishing hydrogen for ‘market preparation’ as the ‘fuel of the future’ under the Clean Energy Partnership (CEP) [3,86].

The third phase of this plan is from 2011 to 2016 [86]. In this part, CEP is focusing on the following objectives:

- preparation for the market, with large-scale operation of FCEVs by customers
- optimisation of vehicle efficiency, performance and reliability
- engagement of new partners and development of the CEP in other regions
- increasing the number of FCEVs
- continuing development of the network of hydrogen refuelling stations
- production of hydrogen from renewable energy sources

The European HyWays project in Phase II focused on commercialisation of 10,000 vehicles (2010–2015), and Phase III contains three sub-phases: 500,000 vehicles from 2015 to 2020, four million vehicles from 2020 to 2030 and 16 million vehicles from 2025 to 2035 [69].

Table 5 presents the 53 hydrogen fuelling station in Europe classified according to hydrogen production category. These stations are spread across 17 countries, which included seven fuel cell bus networks [76] and various energy sources are used to run the stations. As a leader in fuel cell and hydrogen (FCH) technology, Germany has the highest number of stations in Europe with 22 stations (42%), followed by the UK with four stations (7.7%), and then Norway, Denmark and France with three stations each (5.7% combined).

The Sachsendamm fuelling station in Berlin is the largest hydrogen station in Europe. It opened in 2011 and dispenses 200 kg H_2/h. Linde is responsible for supplying the hydrogen, which comes from a green hydrogen source, and storing it underground using a 17.6 m^3 liquid hydrogen tank. The system is equipped with two cryogenic pumps and two dispensers with a 100 kg/h supply capacity. The station is capable of filling about 250 HFC vehicles per day, but is currently used primarily for demonstrations and research, and fuelling around 20 demonstration vehicles per day [87].

The second-largest hydrogen fuelling station is the Total-BVG H_2 fuelling station, which is located in Berlin, Germany. The Total-BVG hydrogen fuelling station was opened in 2002 and uses two methods of hydrogen production: liquid hydrogen delivery and on-site hydrogen generation, using a PEM electrolyser [88]. The station is used to fuel HICE buses from MAN and fuel cell buses. In 2007, a liquefied gasoline gas reformer was added to the station, which has enabled it to produce enough hydrogen to fuel seven buses. The station is equipped with a high-pressure electrolyser, liquid hydrogen storage tank, dispensers for liquid tanks and a compressed hydrogen cylinder using 350 und 700 bar system [88].

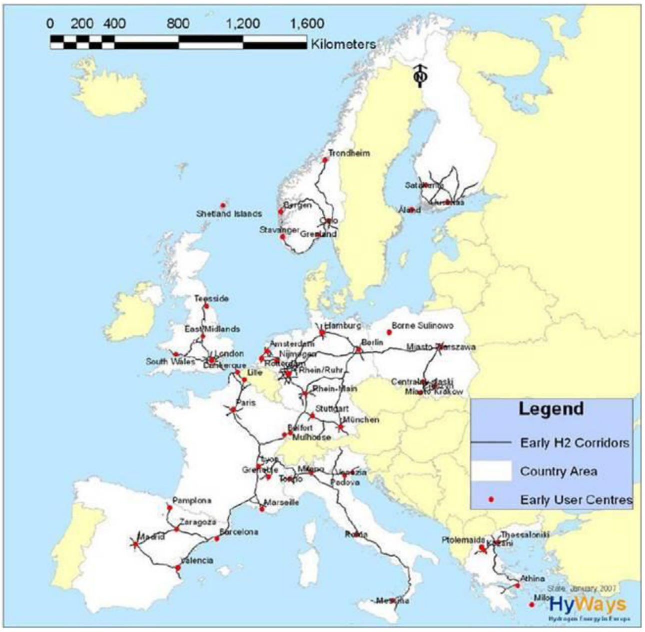
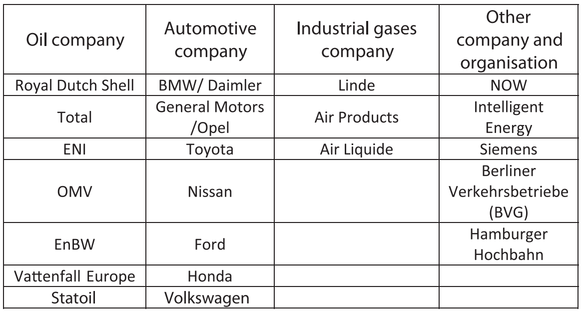


Fig. 12. The Europe early user centres and early hydrogen corridors [69].



Oil company	Automotive company	Industrial gases company	Other company and organisation
Royal Dutch Shell	BMW/ Daimler	Linde	NOW
Total	General Motors /Opel	Air Products	Intelligent Energy
ENI	Toyota	Air Liquide	Siemens
OMV	Nissan		Berliner Verkehrsbetriebe (BVG)
EnBW	Ford		Hamburger Hochbahn
Vattenfall Europe	Honda		
Statoil	Volkswagen		

Fig. 13. The Clean Energy Partnership in Germany consisting of oil, automotive, industrial gas and a number of other companies [3,86].

Some 28% of the hydrogen stations in Europe use zero emission energy sources (Table 6). These stations are spread across seven of the 17 European states that have hydrogen fuelling stations. Five of these stations are in Germany, which has a total of 22 stations. Norway, the UK and Denmark each have two zero-emission stations, and Greece, Sweden and Iceland each have one. The other 46% of hydrogen stations use hydrogen production sources that have GH emissions (that is, employ steam methane reformers or other fossil fuel energy sources and conversion processes).

The hydrogen station in Pontypridd, Wales, is zero-emission generating hydrogen from water electrolysis powered by PV arrays. The Pontypridd station was prepared with 20-kW Kyocera photovoltaic modules, which are installed on the roof of the hydrogen centre, and a 21.5 kg/day (10 Nm^3/h) Hydrogenics alkaline electrolyser. The generated hydrogen is compressed to 200 bar and stored in a 350-bar storage tank. The compressed hydrogen is used to fuel a University of Glamorgan fuel cell minibus, and to generate electricity for the building using a 12-kW hydrogenics PEM fuel cell. The project, developed by the University of Glamorgan, was established in 2008, and focuses on the development and demonstration of hydrogen energy technology, and raising awareness of hydrogen as a clean and sustainable energy [89]

Table 5
Hydrogen fuelling stations in European States (delivery and on-site production) (main sources: [64,68,73,76]).

Station type	Country																	
	Germany	Norway	UK	Italy	Denmark	Greece	Sweden	Iceland	France	Belgium	Czech Republic	The Nether-lands	Luxemburg	Portugal	Spain	Austria	Switzer-land	Total
On-site hydrogen production	11	2	2	3	3	1	1	1	2	2	1	1	0	0	1	0	0	31
Stations with hydrogen delivery	11	1	2	0	0	0	1	0	1	0	0	1	1	2	0	2	0	22
Total	22	3	4	3	3	1	2	1	3	2	1	2	1	2	1	2	0	53

Table 6
Relatively low GH emission hydrogen fuelling stations in European States (main sources: [64,68,73,76]).

Station type	Country																	
	Germany	Norway	UK	Italy	Denmark	Greece	Sweden	Iceland	France	Belgium	Czech Republic	The Netherlands	Luxemburg	Portugal	Spain	Austria	Switzerland	Total
RN energy	5	2	2	1	2	1	1	1	0	0	0	0	0	0	0	0	0	15
Low to medium GH emission	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High GH emission	17	1	2	2	1	0	1	0	3	2	1	2	1	2	1	2	0	38
Total	22	3	4	3	3	1	2	1	3	2	1	2	1	2	1	2	0	53

HyNor Oslo hydrogen station in Norway is part of the ‘Hydrogen Road of Norway’ project, which was established in 2003. The Oslo hydrogen station was opened in 2012 and uses a zero emission energy source to produce hydrogen from water. The station is equipped with two Hydrogenics electrolysers, which are capable of providing 260 kg H_2/d.

The produced hydrogen is then stored in six cylinders with a total volume of 12 m^3 at 440 bar, and used to fuel five fuel cell buses carrying 350-bar storage tanks system on regular public transport routes [90]. The system uses two diaphragm hydrogen compressors in parallel. The proposed Hydrogen Road of Norway, of which this station is a part, is expected to decrease noise and improve air quality in the Oslo area and decrease harmful emissions from public transport.

4.4. Hydrogen fuelling stations in Asia

In total nine Asian countries have built or intend to build hydrogen fuelling stations (Table 7). Currently, there are only about 35 stations in four Asian countries, and most of these are spread across Japan and Korea—23 in Japan and 12 in Korea. The other seven stations are located in China, which has three, Singapore, which has two, and Hong Kong and Taiwan, which each have one. There is one station in India, which is used for the three-wheeler fleet of Mahindra; another one is planned for the future (main sources: [64,68,73–75]). Turkey and Pakistan are expected to enter the hydrogen technology competition and build hydrogen stations in the next few years (Figs. 14–16).

Fig. 17 shows four major cities prior to the start of building fuelling station and marketing FCEV in 2015, with focus on the hydrogen stations in areas with more likely FCEV customers. More stations will be built in the highways linking these cities together and enabling people to travel between the cities [91].

The Fuel Cell Commercialization Conference, convened in Japan in 2010 (FCCJ), proposed a four-phase plan to make the FCEV and hydrogen station business workable by 2026. This plan is focused on the market and technology, with the goal of full commercialisation by 2026. To achieve this goal, a significant promotional program is being implemented with close cooperation and alliance between public and private entities with regard to technology development, revision of regulations, and continued financial support towards market formation [70,92].

In 2012, the Japanese government declared plans to initiate deployment of hydrogen vehicles and infrastructure through the commercial introduction of FCEVs in 2015 and the establishment of a base infrastructure and sustainable business model, consisting of 100 hydrogen stations by 2015 [3] (Fig. 17). In conjunction with this plan, Japan has started constructing the first commercial hydrogen stations in Nagoya at September 2014 [93]. Furthermore, they have allowed industries and academies to play a role in revising hydrogen-related safety regulations in addition to developing new technologies and activities. The hydrogen infrastructure will focus on Tokyo, Nagoya, Osaka and Fukuoka, and connections between these cities. Honda has built a production line for FCEVs, as has Toyota for its Concept FCV-R, which is expected to be ready for sale in the USA from 2015. Toyota in conjunction with Nissan and 13 other Japanese companies intends to supply hydrogen fuel for FCEVs under the direction of JX Nippon Oil [22,23].

In addition, this plan will carry out technological demonstrations of FCVs and hydrogen supply infrastructure under conditions close to actual use as well as social demonstrations verifying user-friendliness, business-launch ability and social receptivity, towards full commercialisation of dissemination of FCVs to general users in 2026.

Currently there are three hydrogen FC bus networks in Japan [94–96] and Haneda Hydrogen Station is a part of this network. Haneda was station constructed in 2010 and is used to fuel Hino's FCH buses on a commercial route between central Tokyo and Haneda Airport. Haneda Hydrogen Station is attached to a natural gas station and generates hydrogen on site using a steam reforming and production process followed by CO_2 capture. The station is equipped with 18 cylinders of 300 l each, for storing compressed hydrogen under 400 bar, which are operated by Tokyo Gas under contract to the Hydrogen Research Centre. The fuel cell buses use a 350-bar fuelling system. The project is part of the Ministry of Economy, Trade and Industry's Demonstration Program for Establishing a Hydrogen-Based Social System [64].

In terms of clean hydrogen production stations in Japan, the Yakushima station was built in 2004 and is part of the Zero Emissions Project led by Kagoshima University and Yakushima Denko Co [64]. The Yakushima station uses electrolysis and hydroelectric power to produce hydrogen from water. Honda FCX FCV with a 350-bar fuelling system is used.

South Korea has clearly shown, through its national research and development (R&D) preparations for hydrogen and fuel cell developments during the past years, that it is well positioned among the world's hydrogen industries. Over the next few years, Korea's hydrogen road map will involve a three-phase plan for encouraging FCEV hydrogen technology and hydrogen infrastructure. It began in 2009 and aims for FCEVs to be fully commercialised and deployed by 2030 (Ministry of Knowledge Economy, 2009). The Korean government has targeted the operation of over 160 hydrogen fuelling stations across the country by 2020 and has invested $330 million in the initial fuelling network and FCEVs in cooperation with the auto industry (Kia and Hyundai). As part of the hydrogen infrastructure road map, the Korean government announced in 2010 that it would open 43 stations by 2015, 168 stations by 2020 in the second phase, and 500 stations by 2030 in the third phase [75].

Government and car industry R&D into hydrogen and fuel cells over the past years has placed South Korea among the leading nations in hydrogen-powered transport [75].

Daejeon hydrogen station is one of 12 hydrogen stations that use hydrogen production with environmental effects. There are seven stations using hydrogen delivery, four stations using an SMR and one using an on-site electrolyser to generate hydrogen. This station was built in 2006 and uses compressed hydrogen with a 350-bar fuelling system. The station is capable of producing 65 kg per day and uses a 350-bar pressure fuelling system to serve approximately 20 FCEVs per day [64]. Daejeon Station is used by the Korea Institute of Energy Research for hydrogen for FCH infrastructure research.

The Hwaseong hydrogen station is the largest fuelling station with a fuelling capacity of 45 FCEVs per day. It uses 350- and 700-bar fuelling systems and it was opened in 2008 by Hyundai Motor

Table 7
Relatively low GH emission hydrogen fuelling stations in Asia (delivery and on-site production) main sources: [64,68,73–75].

Station type	Country									
	Japan	China	South Korea	India	Singapore	Hong Kong	Turkey	Pakistan	Taiwan	Total
On-site hydrogen production	18	2	5	0	2	0	0	0	0	27
Stations with hydrogen delivery	5	1	7	0	0	1	0	0	1	15
Total	23	3	12	0	2	1	0	0	1	42

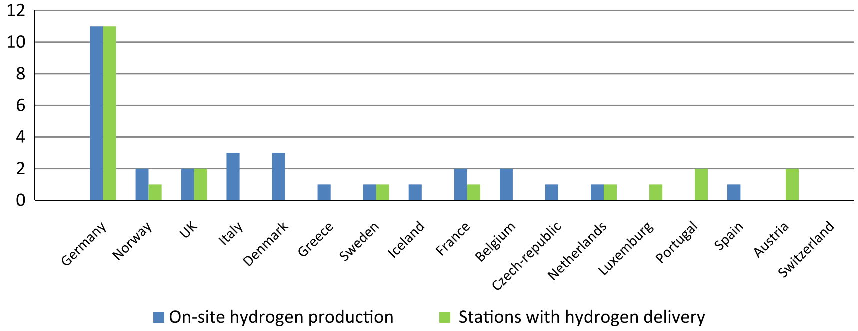


Fig. 14. Hydrogen fuelling stations in European States by type (delivery and on-site production) (main sources: [64,68,73,76]).

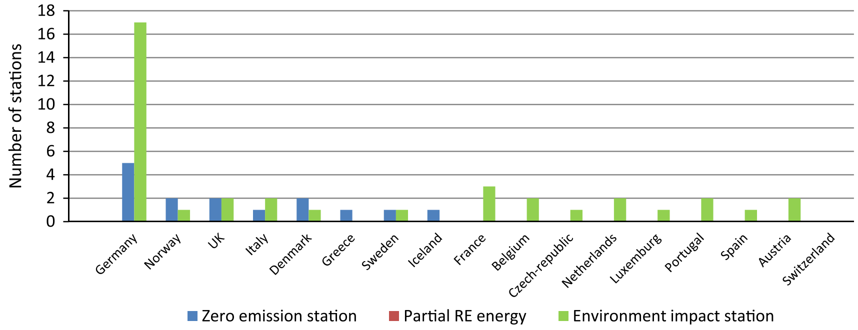


Fig. 15. Hydrogen fuelling stations in European States (production types). Main sources: [64,68,73,76].

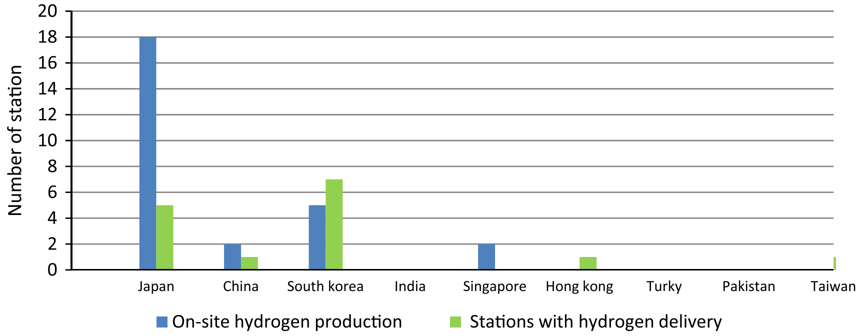


Fig. 16. Hydrogen fuelling stations types in Asia. Main sources: [64,68,73–75].

Co (HMC). The hydrogen is delivered to the station as compressed gas by truck.

The Expo hydrogen fuelling station in China is the biggest hydrogen and fuel cell hydrogen vehicle demonstration for public transport worldwide. It was built in 2010 in Shanghai International Automobile City, situated northwest of Shanghai. The station is designed to fuel a fleet of 196 FCEVs consisting of six FCE bases, 90 FCE cars and 100 FC sightseeing cars. There are four dispensers with seven nozzles using a 350-bar fuelling system. The hydrogen is stored at 430 bar in 15 cylinders, each of which can store 300 kg of hydrogen for a total of 4500 kg. There are two companies using by-product hydrogen resources to provide the station with hydrogen: Shanghai Baoshan Iron & Steel Corporation (SBISC) and Shanghai Coking & Chemical Corporation (SCCC).

South Korea is a leader in FCH technology among Asian countries and it has made remarkable progress in FCEV technologies (Table 8).

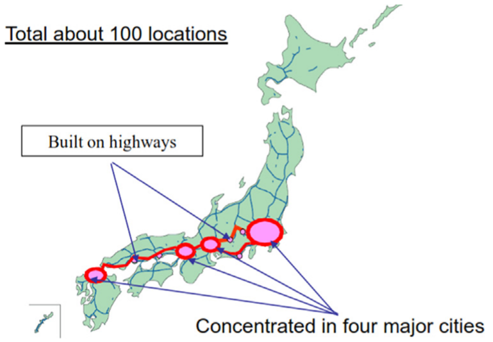


Fig. 17. Hydrogen fuelling stations in Japan [91].

5. Conclusions

Fuel cell electrical vehicles and hydrogen stations represent an important aspect of hydrogen technology that can help reduce GHG, contribute positively to achieving the goals for global energy sustainability and energy security, and hence improve the world's prospects for sustainable development into the future.

This paper has reviewed the technical state of the art and economics of the main hydrogen production methods. Coal gasification is the most common and cheapest production process, at \$1.8–2.9/H_2kg and 2.3–5.8/H_2kg for SMR. But it leads to GHG emissions and hence cannot be a truly sustainable option in the

Table 8
Hydrogen stations in Asia (production types) main sources: [64,68,73–75].

Station type	Country									
	Japan	China	South Korea	India	Singapore	Hong Kong	Turkey	Pakistan	Taiwan	Total
RN energy	1	0	0	0	0	0	0	0	0	1
Low to medium GH emission	0	0	0	0	0	0	0	0	0	0
High GH emission	22	3	12	0	2	0	1	0	0	41
Total	23	3	12	0	2	0	0	0	0	42

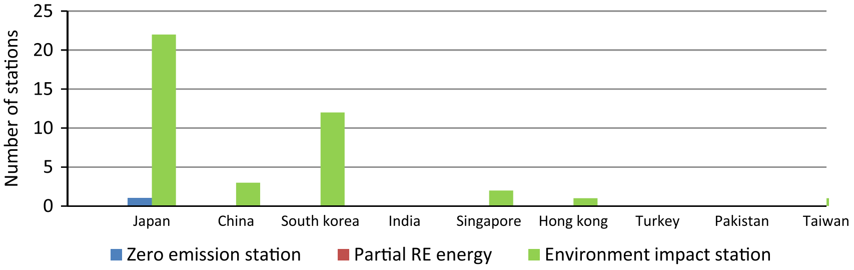


Fig. 18. Hydrogen stations in Asia (production types). Main sources: [64,68,73–75].

long term. Hydrogen derived from a water electrolyser using RE input (solar PV) can now attain a unit cost as low as \$6.3–25.4/H_2kg depending on the cost of the PV system, while that from wind power can be even lower \$6–7.4/H_2kg. Taking into account the relative energy efficiencies of hydrogen fuel cell and gasoline internal combustion engines (assumed to be on average 50% for FCEV and 30% for petrol ICE), this hydrogen cost corresponds to a gasoline cost of \$1.7 /litre. The price of unleaded regular gasoline in the USA currently is around \$0.92/litre, while in Western Europe it is typically in the order of \$1.14–2.57 /litre. Hence hydrogen from renewables is not so far from economic competitiveness today, with further cost reductions likely as key technologies such as PEM electrolysers come down in cost with higher volume production.

The paper has also reviewed the state of deployment of hydrogen fuelling stations around the world. Currently, on-site hydrogen stations use two main methods to produce hydrogen: small SMR and hydrogen from electrolysers.

In 2013, there were about 224 working hydrogen stations around the world, spread over 28 countries. About 43% of these stations are located in North and South America, 34% in Europe, about 23% in Asia and nothing in Australia. Most of the stations are built in the USA with 94, Japan with 23, Germany with 22 and Korea with12 stations. Around 49% of these stations used on-site hydrogen production, 26% of these stations use hydrogen made somewhere else (delivery) and 25% of the stations are not identified. Around 13% of the stations used a renewable energy source to produce hydrogen. Most of the zero-emission hydrogen stations are located in the USA and Europe, with only one station in Japan. The numbers of new stations being built from 2009 to 2012 were three stations in the USA, one in Europe and nothing in Asia; however, Japan announced to start producing the first commercial hydrogen stations this year.

A number of leading automotive manufacturers have announced plans to start marketing FCEVs in 2015. Hence the momentum for building a network of hydrogen fuelling stations is likely to increase over the coming years, since the availability of convenient hydrogen refuelling facilities must go hand in hand with the introduction of hydrogen fuel cell vehicles.

Hydrogen station networks can be found already or are planned in several cities around the world, but the number and the hydrogen delivery capacity of these stations will only be sufficient to serve a relatively small number of HFCVs. For example, the largest public hydrogen station network in the world serves in Los Angeles and San Francisco, comprising 17 stations (CFCP, 2013) for a total fleet of hydrogen vehicles of around 1400. The station for passenger cars with the highest capacity of more than 161 kg H_2/day is in Phoenix, Arizona, which can refuel up to more than 40 vehicles per day, while AC Transit Emeryville, California, is a companied station with a capacity of 240 and 360 kg H_2/day for passenger cars and buses, respectively.

Germany has the most developed nationwide hydrogen infrastructure in Europe, with 16 stations, which serve more than 110 FCEV on the road and another 50 stations will be completed by 2015.

Currently there are 14 hydrogen fuelling operating stations in Japan, serving 37 FCEVs.

The hydrogen network in South Korea consists of 13 stations in different cities serving 100 public FCEVs.

The hydrogen fuelling networks for fuel cell buses are generally more developed. For example, in North America there are ten hydrogen fuel cell bus networks in different areas, which serve around 44 buses. Europe currently has seven fuel cell bus networks serving more than 26 fuel cell buses, and there are three hydrogen FC bus networks in Japan serving five buses.

Hence, while hydrogen station networks to serve FCEVs and buses are now starting to appear around the world, they will only be able to serve relatively small hydrogen vehicle fleets. If hydrogen vehicles gain market acceptance and demand for them grows, it will therefore be essential to expand the hydrogen fuelling networks accordingly. It makes most sense from an economic perspective, as well environmental and social points of view, that hydrogen station networks are planned to be in place at the same time as the sales of FCEVs and hydrogen fuel grow. Such matching of capacity with demand is clearly preferable to having increasing numbers of FCEVs with few places to refuel them, or a large capacity of hydrogen stations without enough FCEVs to use the fuel they can supply (Fig. 18).

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