INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 45 (2020) 28217–28239

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Review Article

Is the H_2 economy realizable in the foreseeable future? Part III: H_2 usage technologies, applications, and challenges and opportunities

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HIGHLIGHTS

- Industrial applications of H_2 with a focus on decarbonization of industry.
- H_2 usage through fuel cells for mobile and stationary applications.
- Combustion of H_2 in internal combustion engines and gas turbines.
- Major challenges and opportunities towards realizing H_2 economy.

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https://doi.org/10.1016/j.ijhydene.2020.07.256

ARTICLE INFO

Article history:
Received 30 May 2020
Received in revised form
27 July 2020
Accepted 29 July 2020
Available online 21 August 2020

Keywords:
H_2 application
Combustion
Industrial
Fuel cells
H_2 society

ABSTRACT

Energy enthusiasts in developed countries explore sustainable and efficient pathways for accomplishing zero carbon footprint through the H_2 economy. The major objective of the H_2 economy review series is to bring out the status, major issues, and opportunities associated with the key components such as H_2 production, storage, transportation, distribution, and applications in various energy sectors. Specifically, Part I discussed H_2 production methods including the futuristic ones such as photoelectrochemical for small, medium, and large-scale applications, while Part II dealt with the challenges and developments in H_2 storage, transportation, and distribution with national and international initiatives. Part III of the H_2 economy review discusses the developments and challenges in the areas of H_2 application in chemical/metallurgical industries, combustion, and fuel cells. Currently, the majority of H_2 is being utilized by a few chemical industries with >60% in the oil refineries sector, by producing grey H_2 by steam methane reforming on a large scale. In addition, the review also presents the challenges in various technologies for establishing greener and sustainable H_2 society.

Contents

Introduction

All major sectors in the hydrocarbon economy can progress towards decarbonization with a deployment of H_2 technologies. H_2 economy can be attained through the large-scale integration of renewable energies and intermittent power generation with the production of green H_2 as described in Part I of this review series [1]. Once the cleaner H_2 production technologies mature in the near future with commercial viability ($1.5 to 3 per kg H_2), most likely through water electrolysis and/or steam methane reforming (SMR) with carbon capture and storage (CCS), a significant deployment into mass markets is very likely to occur [2]. H_2 also enables the distribution of energy not only to end-users such as refueling stations but also to various industrial sectors by road, pipelines, and ocean in solid, compressed, or liquid forms, as detailed in Part II of the review series [3]. The role of stored H_2 at large scale (underground or in the gas grids blended with natural gas) to increase the energy system resilience is expected to evolve together with the penetration of renewable energies in the power generation mix. The major goal of Part III of the H_2 economy series is to review how H_2 will contribute to achieve the zero-carbon footprint of sectors such as transportation (light and heavy-duty on-road, rail, and ship), industry, and buildings (heat and power), as well as its use as feedstock in industries such as chemicals, refineries, or steel. Fuel cell stacks are matured enough for commercialization and durability has been generally proved such as in London's buses with over 25,000 h operation. Thus, the most significant challenge for a massive deployment is to reduce stack and system costs, which will require both economies of scale (increased productions) and further technology developments to reduce material costs, typically the load of catalyst precious metals. The use of fuel cell stacks in heavy-duty applications is promising a vast market in the next decade, not only in road transport but also in trains (such as the recent Alstom iLint FCH train with 400 kW FC) and ships. Moreover, green H_2 from large-scale renewable electrolysis and SMR/CCS will play an essential role to decarbonize industry, replacing the grey H_2 currently used in the refining and ammonia production industry. Clean H_2 is also expected to replace fossil feedstock such as coke in steel manufacturing, and to progressively replace natural gas for heat and power generation.

The scope of Part III of the review series is shown in Fig. 1, where the realization of H_2 economy in a sustainable manner in the foreseeable future for various applications is presented. As seen on the left-hand side of Fig. 1, H_2 can be effectively utilized for applications comprising industrial processes as a hydrogenating agent, fuel cells (FC) as a direct anode fuel as well as in the combustion process as a feedstock. Major H_2 consumers are the industrial processes related to ammonia production and oil refineries where H_2 is produced by steam methane reforming in large-scale. As the cleanest energy conversion devices, low-temperature FCs use relatively pure H_2 as fuel, being utilized for transportation and stationary applications. With its high gravimetric energy content, H_2 is also being considered as a cleaner fuel for gas turbines, internal combustion engines, and as a direct fuel for thermal energy applications. As shown in Fig. 1 (right-hand side), the review also brings out the major issues associated with large-scale H_2 production and distribution along with market potentials and opportunities for commercialization with the aim of developing a sustainable and secure H_2 society [4,5].

Industrial uses of H_2

H_2 is widely used in industry, with consumption of ~70 million tons per year in 2019 in pure form (about 6% of the natural gas use) and another 45 million tons as syngas, according to the International Energy Agency (IEA) [6], as shown in Fig. 2(a–d). It is, therefore, an established industrial gas being part of the global industrial business. The production market of H_2 for industrial uses was valued at $115 billion in 2017 and is expected to grow to $155 billion in 2022 [7,8]. The H_2 production market is typically divided into "merchant" H_2 for delivery to customers (central generation of H_2 to be sold/distributed by tanks, trucks or pipeline), and "captive" H_2 (on-site H_2 generation at a given facility to be consumed for internal uses). Focusing on the chemical and process industry [9], H_2 is a fundamental reactant in the refining industry and for ammonia production, and therefore fertilizers. Over 27% of the H_2 produced globally is used for ammonia synthesis, refineries use ~33%, methanol producers use ~10%, and over 6% are used by other industries [6]. It is worth mentioning that other chemical industries such as chlor-alkali are producing large quantities of H_2 as a by-product, and the potential for integrating a FC based power generation plant to reduce the industry's electrical consumption has been proven to be a reality [5,10–12].

Ammonia production

Ammonia is industrially produced by combining H_2 and N_2 by the reaction of $N_2 + 3H_2 \leftrightharpoons 2NH_3$, with the rate-determining step of dissociative chemisorption of N_2 on the iron catalyst surface (Fe_2N and γ-Fe_4N), through the Haber-Bosch process. In general, both reactants are produced on-site: N_2 by low-temperature separation of air, and H_2 mainly from natural gas steam reforming (thus "captive" H_2). The industrial process conditions are 250–350 bar and 450–550 °C with α-Fe (ferrite) as a catalyst. Overall, 90% of the ammonia production is used for the fertilizer industry, although it is also used as a refrigerant in refrigeration plants (R-717). In the early 20th century, large hydropower driven alkaline electrolyzers were used to produce H_2 for ammonia synthesis. For example, a 165 MW electrolyzer with 37,000 m^3 H_2/h was operated at Aswan in Egypt [13].

Oil refining

Oil refineries are the largest consumer of H_2, which is produced on-site mainly from natural gas reforming as "captive" H_2, with over 33% share of the global H_2 production [6]. H_2 is used for the processing of intermediate oil products by hydrogenation reactions usually using nickel, palladium or platinum catalysts, as well as for the processing of crude oil into refined fuels (diesel, gasoline, and jet fuel) by hydrocracking and hydro-desulfurization [14,15]. Hydrocracking

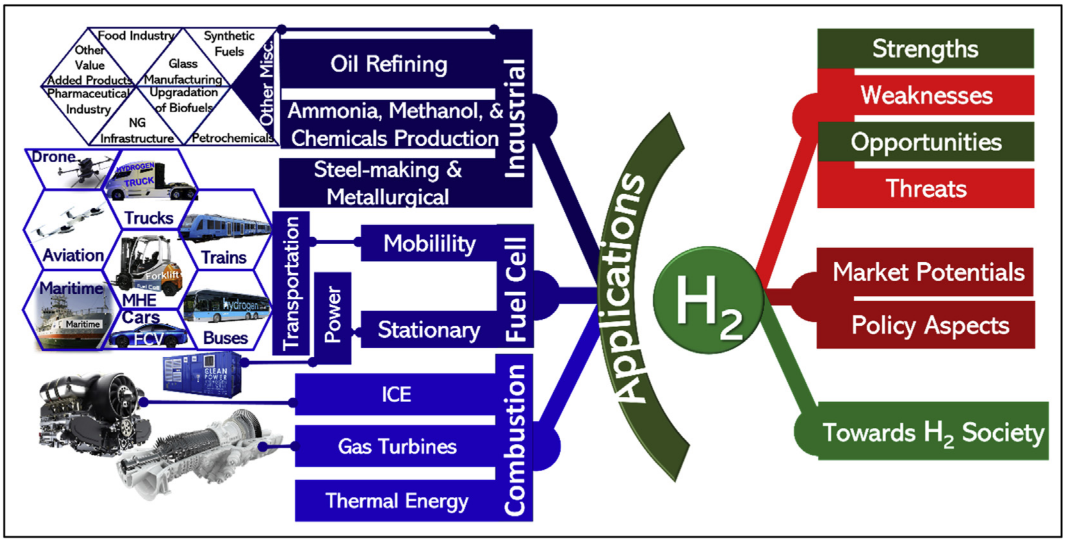

Fig. 1 – Schematic representation showing the scope of Part III of the review including H_2 usage, applications, challenges and opportunities.

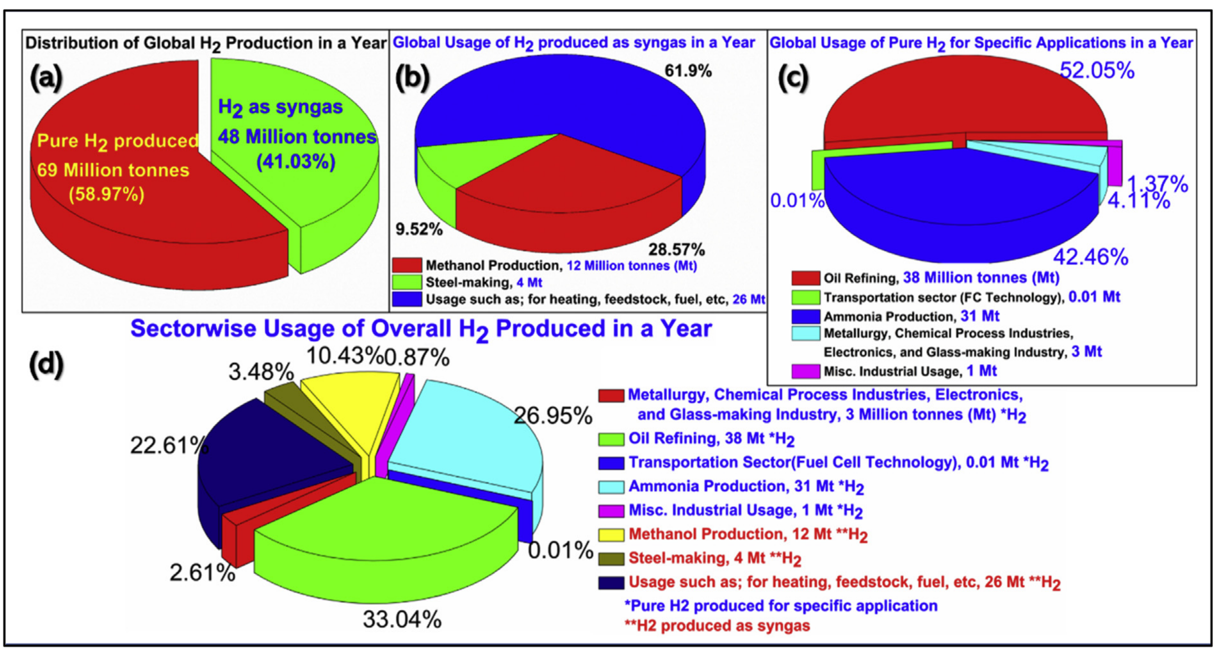

Fig. 2 – (a) Global H_2 production per year as pure H_2 and as syngas, (b) global usage of H_2 as syngas, (c) global usage of pure H_2, and (d) sector-wise usage of H_2 [6].

takes place at 70–150 bar and 400–800 °C depending on the nature of the feedstock. Strict regulations requiring low sulfur in diesel together with the increase in the feedstock containing lower-quality heavy crude oil has increased the H_2 use in refineries. Recent efforts are being carried out to introduce clean H_2 generation into refineries. The FCH-JU has funded the REFHYNE project to supply clean refinery H_2, operating the world's largest H_2 electrolyzer (10 MW, producing 1300-t of H_2/year) in the Shell Rhineland Refinery in Wesseling, Germany and design studies are underway to scale up to 100 MW level [16].

Methanol production

The production of methanol, mainly by the catalytic hydrogenation of carbon monoxide ($CO + 2H_2 \rightarrow CH_3OH$; $\Delta H = -90.7$ (kJ/mole)), accounts for 10% of the global H_2 use. The industrial process conditions are 50–100 bar and 250 °C. Renewable methanol as a liquid fuel has been proposed as another carbon-neutral energy vector in parallel to H_2 [17]. Other industrial-scale methanol production methods (synthesis, gasification, reforming), can be used to cover the rising demand of this fuel. Methanol can be used in transportation applications, directly in internal combustion engines or by blending with gasoline and diesel to reduce emissions. It must be mentioned that methanol has proved its applicability in transportation being used directly as a fuel in methanol fuel cells (DMFC) or after on-board reforming in proton exchange membrane fuel cells. Also, methanol is a raw material used to synthesize formaldehyde (CH_2O), acetic acid (CH_3COOH), dimethyl ether (DME, CH_3OCH_3), and other chemicals.

Several projects have tried to find the best production method for methanol or to demonstrate its suitability for various applications. Obtaining green methanol is a subject of many projects, such as Power2Me [18,19], MefCO$_2$ [20], and Djewels projects [21]. The last-mentioned project started in January 2020 with the main goal to demonstrate the operational readiness of a 20 MW electrolyzer for the production of green fuels (green methanol). It will bring the technology close to the commercial stage (TRL 8) and will be the basis for scaling up the system to 100 MW. Several applications are expected at the end of the projects that deal with methanol usage, i.e. a small scale H_2 generator (NEMESIS2 project) [22], an auxiliary power unit (METAPU project) [23] or light transport vehicles [24,25].

DME and other renewable fuels to H_2 supplement

DME can be synthesized from syngas ($2CO + 4H_2 \rightarrow CH_3OCH_3 + 2H_2O$) or dehydration of methanol ($2CH_3OH \rightarrow CH_3OCH_3 + H_2O$). In addition to being a cleaner and efficient fuel in diesel engines, DME also has multiple uses as refrigerant, a propellant for spray cans, household fuel, solvent, and methylation agent in the chemical industry. In the past 15 years, there has been a huge demand for DME, from 150 kT/year worldwide to more than 2000 kT/year only in China [26]. When DME is obtained from methanol, it can be used successfully in diesel engines for trucks and heavy-duty applications due to water removal. In the BioDME project [27,28], Volvo used DME fuel in diesel trucks for driving more than 1,500,000 km, so the project has been considered a success story. DME can be used in stationary applications, and has been used as household fuel (stove, heating) in China since 2004 [29]. A 20% blend in liquefied petroleum gas or natural gas can be used without any modification of the appliances.

H_2 reduction/hydrogenation

H_2 treatment or hydrogenation is a well-established process in the food industry and organic chemistry. Moreover, H_2 is used in the tungsten and molybdenum refining process in order to avoid carbide formation during the reduction process. The reduction of iron ore offers a huge potential for green H_2 to reduce greenhouse gas (GHG) emissions in steel production. SSAB, a Swedish steel producer, and Vattenfall, a leading European energy company, jointly planned to demonstrate the world's first fossil-free steelmaking technology by 2025 [30].

Fuel cells

H_2 is also postulated as a solution to ensure electricity towards the future low carbon system since it is employed as a reagent in the FC technologies [31]. FC technologies are a critical and indispensable element, enabling secure and suitable energy transition in a cost-effective and environmental way [32,33]. Any emissions are related to the way H_2 is produced. Comparing with other technologies, the FC has higher electrical efficiencies (Tables S1 and S2) [34,35]. As seen from Table S3, it can be observed that research on H_2 utilization (FCs in this case) has been extensively pursued in comparison with production or storage. It can also be observed that research on H_2 in China is significantly most active, leading all the three technologies (also observed in Fig. 2(b) Part I of this series) [1], followed by the USA and Japan.

Transportation applications types

Fuel cell electric vehicles

Comparing to Li-ion battery electric vehicles (BEV), FCEVs have excellent performance in terms of driving range as well as fuel refilling time (~3–5 min). However, as the BEVs have superior grid-to-wheel efficiency and can be recharged either overnight at home or at commercial recharging stations, their commercial adaption has progressed much further than that of FCEVs. When considering the emissions associated with the manufacturing process, FC production is less energy-intensive than batteries which in addition involves more hazardous materials in the manufacturing [36,37]. Proton exchange membrane (PEMFC) is the preferred technology for FCEVs [38–40]. As shown in Table 1, various countries have established technical targets for the development of PEMFCs for FCEVs [41–45].

It has been observed that the FC system should be designed for the FCEVs meeting cold-start ability (<30 s from -30 °C) and durability (5000 h) (Table 1), as well as the driving range per filling, acceleration (0–100 kmph in <10 s) with the FC system power density as high as 7300 W L^{-1} [46]. Consumer FCEVs are close to the target of 5000 h of operation [47,48]. In addition, a typical configuration of the FCEV powertrain is the fuel tank, fuel processor, FC subsystem, DC-DC converter, motor inverter, traction motor, and transmission [38]. In fact, high-performance FCs are being produced by Hyundai, Toyota, Honda, and GM to be used on their vehicles [38,40]. With 100,000 and 500,000 FC units per year, the total system cost is projected to hit \$50 and \$45 per kW_{net}, respectively, for light-duty vehicles with 80 kW_{net} fuel cell stack [49].

In a study conducted with a volunteer group for examining driver acceptance of H_2 powered FCEVs, it was found that ~75% of them would be willing to pay ≤ \$40000 for a FCEV [50] and the adopters of FCEVs are the consumers with high-income owning several vehicles. If FCEVs are to penetrate the mass market, policymakers should find ways to encourage lower-income consumers to purchase them [51]. Due to the R&D activities, the PEMFC technology has achieved the technology readiness level and, therefore, automakers such as Toyota, Honda, and Hyundai have started selling and leasing their FCEV models with the yearly update, in various regions depending upon the H_2 refueling stations (HRS) infrastructure [52]. The specifications for the latest production FCEVs are compared in Table 2 [53–55]. The range per H_2 filling is well above 300 miles, which is much higher compared to battery-operated EVs.

Table 1 – Technical targets for PEMFCs from DOE (USA), NEDO (Japan), FCH JU (EU), and MOST (China).

Parameter	DOE (USA)		Assessments related to DOE (USA) –Targets [43]	NEDO (Japan)		FCH JU (Europe)		MOST (China)	
	2020 [42]	Ultimate Targets [42]		2020 [44]	2030 [44]	2020 [41]	2030 [41]	2020 [45]	2030 [45]
Peak power efficiency (%)	65	70	–	60	–	55	–	60	65
Power density (W L^{-1})	650	850	3000 (2035)	4000	6000	7300	10,000	3000	4000
Cold start-up temperature (°C)	−30	−30	–	−30	–	−25	–	−30	−40
Durability (h)	5000	8000	8000 (2050)	>15 years	>15 years	5000	7000	5000	8000
H_2 Filling pressure (MPa)	70	–	–	70	–	70	–	70	70
Cost (per kW)	$ 40	$ 30	$ 30 (2050)	< ¥800	< ¥400	€ 60	€ 40	RMB 1000	RMB 150

Table 2 – Specifications for the latest FCEVs using PEMFC technology.

FCEV/Launch year	Mass (kg)	FC/motor power (kW)	H_2 tank capacity (kg)	Fuel pressure (MPa)	Top speed (mph)	Range (miles)	Fuel consumption (mpg gasoline equivalent)	Battery
Hyundai Nexo Blue/2020	1809	95/120	6.33	70	~110	380	61	240 V Li-ion
Hyundai Nexo Limited/2020	1866	95/120	6.33	70	~110	354	57	240 V Li-ion
Honda Clarity/ 2020	1875	103/130	5.46	70		360	68	346 V Li-ion
Toyota Mirai/ 2019–2020	1848	90/113	5	70	~110	312	67	245 V Ni-MH

Buses, coaches and trucks

As fuel cell cars are facing fierce competition from BEVs, the focus in FCEV development has shifted to heavy-duty applications where central refueling infrastructure can be utilized and where the total power train cost is less than in BEVs. Fast refueling times and high energy density (less weight than BEV), highlights the promising potential of FCEV towards the future of mobility [36,56]. A more stringent durability requirement of 20,000 h (Table S4) for the FC engine has been specified for these heavy-duty applications in comparison to the 5000 h for the FCEVs (Table 1) [41]. The major advantage of fuel cell buses (FCB) is that they lead to a significant decrease in emissions, particularly in larger cities. Europe has been the leading region in the application of FCBs with more than 10 million km driven to date [57]. Fig. 3 shows how the cost of FCBs was reduced by almost a threefold over the last 10 years, while the cumulative number of buses in Europe (UK, France, Germany, Norway, Switzerland, Italy, and so on) rose to 850 [58]. This is expected to increase to 1100 and 1400 by 2024 and 2030, respectively with the cost reaching ~ €500,000 by 2030 [58].

In the USA only 38 FCBs were operating in early 2019 with availability ranging from 52 to 78% [59]. However, the number is expected to go up since more than 39 FC buses are in the developmental phase [60]. The largest number of FC buses is running in California, which is due to their environmental targets and HRS infrastructure [61]. In China, the Government subsidy supports the transportation sector to deploy FC buses. National companies intend to deliver hundreds of FCBs in the forthcoming years which requires a suitable H_2 infrastructure to be built. Korea and Japan have also announced their FCB activities. Even though the numbers are still rather low (37 new FCBs in Korea and 18 running in Japan in 2019), 100 buses were planned to be deployed for the Tokyo Olympics in Japan in 2020 (now stands cancelled due to COVID-19 pandemic), and a substantial increase is expected in both countries [59]. The first FCB program is launched also in India by Tata Motors Ltd [62].

FC trucks are being developed by Toyota, Hino, Daimler, Volvo, Hyundai, Hyzon Motors, and Nikola Motor Company [59,63–66]. It is imperative in urban areas to rely more on H_2 fueled trucks, since diesel trucks will be banned in city centers in many countries. The truck application is even more demanding than the bus. The stack durability goal of 50,000 h and the needed refueling rate is several times higher than the current automotive standard. For example, Hyundai Xcient fuel cell trucks are powered by a 190 kW FC system using two 95 kW stacks taken from NEXO. The seven tanks have H_2 storage capacity of 35 kg, which gives the truck a range of around 400 km. Nikola Motor Co. is developing FC powered heavy-duty trucks, to be launched in 2022 with 1200 km per tank of H_2. Nikola is also planning 700 truck refueling stations by 2028 and it has at least 13,000 preorders for the trucks. Toyota Motor Corp. is working with Kenworth Truck Co. to jointly produce FC powered cargo-hauling trucks for California, with >500 km between H_2 fill-ups.

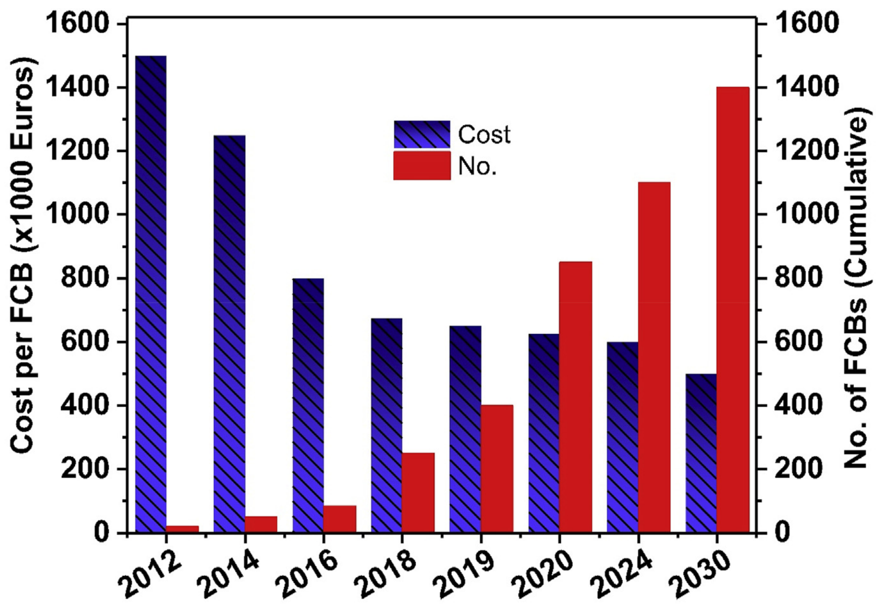

Fig. 3 – Reduction of cost and increase in number of FC buses in Europe.

Trains and trams

H_2 powered FC trains built by Alstom started to regularly operate in Lower Saxony (Germany) in 2018, and recently Coradia iLint by Alstom is successfully tested in the Netherlands [59,67] with a top speed of ~87 mph. A full tank of H_2 provides a range of 1000 km, which is sufficient for an entire day. With further improvements for large-scale production, it is likely that UK and France will also operate FC trains soon. Vivarail (UK) in collaboration with the Arcola Energy [68] and Ballard Power Systems is planning to develop FC powered train in the near future [69]. According to the present plans, the diesel trains will be replaced with FC trains by 2035 and 2040 in France and the UK, respectively [59]. Inlandsbanan (a Swedish train operator) and Statkraft (energy utility company) [70], and Pesa Bydgoszcz SA (a Polish rail vehicle manufacturer) and PKN Orlen (state-owned oil refinery) [71] have signed Letters of Intent to develop FC powered freight trains in their respective countries. Stadler Rail Group, Switzerland will supply the first FC powered train to California in the USA [72]. FC trams are tested in St. Petersburg (Russia), and Foshan (China) [59,73,74]. It is expected that in St. Petersburg the H_2 FC trams will get on the line in 2022/2023. A prototype of these next-generation trains powered by a 400 kW PEMFC is being tested in South Korea, for further commercialization [75]. East Japan Railway Company is utilizing Toyota FC technology to develop a FC powered (180 kW PEMFC) train between Yokohama and Kawasaki, that can operate at ~60 mph [76]. The state-of-the-art and future targets for FC electric trains are summarized in Table S5 [41].

Material handling equipment

Material handling equipment (MHE) is considered as a promising niche market for FC deployment. This category comprises forklift trucks in warehouses and specialty vehicles in airports and harbors. FC powered forklift trucks offer better availability over battery-powered units due to fast refueling and they can be used indoors in contrast to diesel-powered units. Plug Power as the market leader has proven the commercial viability and sold over 20,000 FC forklifts with refueling systems [59]. Plug Power has joined hands with Amazon and Walmart to deploy FC powered forklifts in their fulfilment centers in the USA. While in Europe, Carrefour (leading food retail) has deployed 137 units in northeastern France [77]. The interest in the deployment of FC based MHE by leading companies such as Toyota Motor Corporation, BMW Manufacturing Co., Coca-Cola, FedEx Freight, Mercedes, Procter and Gamble, IKEA, Sysco, and others, indicate that the number of activities for deployment of FC MHEs continues to grow in the global market [78,79]. This promises a transition from diesel-powered material handling systems towards H_2 FC based MHE [59]. Moreover, South Korea is also developing the world's first FC powered construction equipment, where Hyundai Motor Group in partnership with their construction wing aims to produce FC powered excavators at mass scale by 2023 [80]. In Table S6, the state-of-the-art and future targets for forklifts are summarized [41].

Maritime applications

FCs have been used for submarine propulsion for a long time. In 2019 TKMS (Germany) unveiled a 4th generation FC system for submarine applications with tested operational capability of 70,000 h [81] and Navantia is finalizing the construction of the first S80-class submarine with 300 kW FC stacks for the Spanish Navy. More recently, after demonstrations such as the Nemo H_2 passenger boat operating in Amsterdam channels, and the Energy Observer Yacht [82] promoting renewable energy over a seven-year world tour, FCs are considered as auxiliary power units (APU) to support the onboard electric loads (hotel loads) and for the propulsion of all types of marine vessels [83]. The EU through the Horizon2020 program and the FCH JU is supporting maritime FC deployment for prime propulsion or auxiliary loads with 150–600 kW as can be seen in

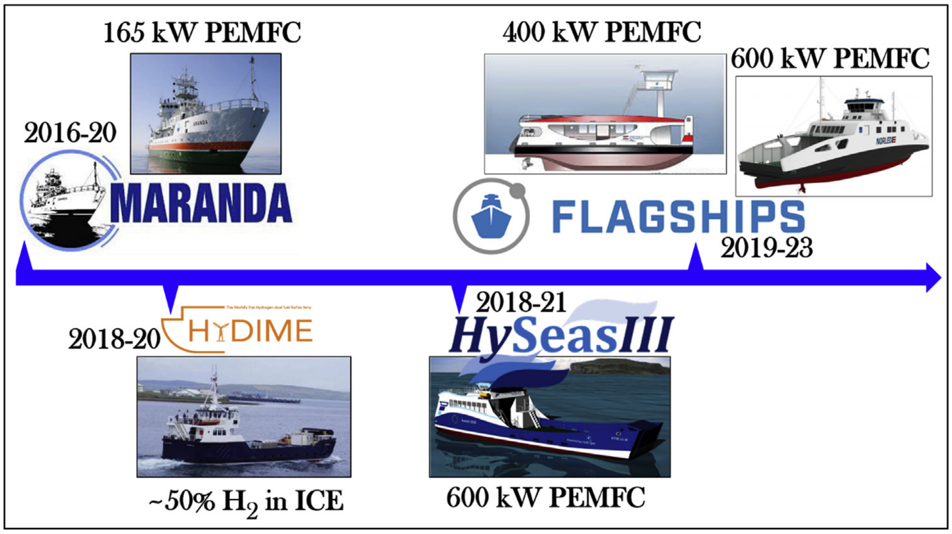

Fig. 4 – Horizon2020 and FCH JU supported projects in H_2-FC propulsion in the maritime sector.

Fig. 4 [58]. Evidently, PEMFC is the most preferred power system for promoting zero carbon footprint, by using pure H_2.

In several countries actions have been undertaken to build H_2-fueled ships and boats [59]. Powercell Sweden AB and Havyard Group (a Norwegian ship technology company) signed a contract to design and develop a FC system comprising of multiple 200 kW FC stacks (collective output 3.2 MW) for installation in one of Havila Kystruten's maritime vessel to be operated in Norwegian waters [84]. In Norway, fuel-cell vessels for 200 passengers and 60 cars are under construction. FC boats for inland waterways are planned in France. Bloom Energy and Samsung Heavy Industries intend to build solid oxide fuel cell (SOFC) powered ships. Hyundai is building FC powered fishing boats.

ABB in collaboration with Hydrogène de France planned to develop megawatt-scale FC powered ships in order to curb the global GHG emissions since shipping constitutes 2.5% of the GHG emissions [85]. Toshiba Energy Systems supplied compact 30 kW FC systems (with increased volumetric power density, ~three times to the stationary model) for powering Japanese maritime vessels [86].

Aerospace applications

FCs have been used to produce space power since the Gemini earth-orbiting mission in 1960s. The Gemini FC was an early version of the PEMFC technology. However, alkaline fuel cells (AFC) were selected for the Apollo program and the following space mission for several decades including the space shuttles [87,88]. However, NASA is considering PEMFC and SOFC technologies for future missions [89]. The space FCs are supplied with cryogenic H_2 and O_2, and the water produced is used by the crew on manned flights. FCs are also studied as a power source for small electric aircraft and as APUs for full-size jet planes. The most recent advances in the technology have been piloted in the HY4, a four-passenger concept plane by the German Aerospace Research Institute DLR [90]. However, the first commercial aerospace application of FCs appears to be drones and UAVs where the flying time and range can be extended over Li-ion batteries. Doosan Mobility Innovation (South Korea) signed agreements with Microsoft, ReadyH2, and SkyFire Consulting (USA) to develop advanced FC powered drones for various applications [91]. HES Energy Systems (Singapore), Hy-Hybrid Energy (Scotland), and Goldi Mobility (Hungary) signed MoU to develop H_2 powered drones [92]. Leading FC companies such as Ballard, Hydrogenics, etc. are developing their offering for this market [93]. The state-of-the-art and future targets for FC electric aircraft are summarized in Table S7. Preliminary findings by the FCH JU and the Clean Sky JU [94] to be published in summer 2020 have shown that H_2 propulsion is the most promising solution for short-to medium-range aircraft in the next 15–20 years [58].

Refueling infrastructure

As a clean energy carrier, H_2 is primarily an alternative fuel in the transportation sector, which accounts for nearly 25% of the global primary energy consumption. The transportation sector faces two major challenges: (i) implementation of infrastructures for H_2 production, storage, transportation/distribution, and (ii) refueling, as well as the development of affordable fuel cell electric vehicles (FCEV). Customers will have no incentive to buy FCEV until a convenient H_2 refueling station network is established, yet it is not commercially viable to construct a large number of HRS without adequate FCEVs, a chicken-and-egg dilemma [95,96]. Therefore, fleet operators (buses, taxies, delivery vans) would be a more natural starting point for infrastructure development rather than FCEVs for private use.

H_2 cannot use the existing distribution network for liquid fuels and requires new propulsion systems and technologies. However, the installation of new H_2 refueling infrastructure involves high investment risks and uncertainties, especially at the early stage of FCEV penetration. In order to overcome this challenge, a collaborative consortium involving infrastructure companies, car manufacturers, and the government can help to share the risks. R&D collaborations between the infrastructure and automotive companies are critical to ensure the simultaneous increase of the HRS and FCEV. Government policies such as subsidies or tax breaks are also necessary to alleviate the high capital cost and long payback period. H_2 infrastructure establishment initiatives are taking place in the USA (California), Europe (Germany) and Asia (Japan). The German H_2 Mobility program has announced investment plans to build 1000 HRS by 2030 [97] and the Japan FC Commercialization Conference planned to build 1000H_2 HRS by 2025 [98]. Even though the FCEVs have a higher retail price than internal combustion engine vehicles, both the fuel (because of higher efficiency) and maintenance costs (with lesser number of rotating parts) are lower.

The safety of H_2 refueling infrastructures also plays a critical role in customer acceptance for FCEVs. As of now, standards for connections, safety aspects, and performance requirements for H_2 refueling and FCEVs have been established through ISO and SAE standards [99]. The state-of-the-art and future targets for HRS are summarized in Table S8 [41].

Stationary applications

Stationary FC applications range from sub kilowatt backup power units to multi-megawatt power stations. As the large units typically use fossil fuels as the primary fuel in combination with high-temperature FC technology (SOFC, molten carbonate fuel cell (MCFC)), they are not discussed in detail here.

Micro-CHP

The most wide-spread FC application is domestic combined heat and power (CHP) units or better known as micro-CHP systems. In 2014, the Japanese (m-CHP) ENE-FARM project passed 100,000 sold systems, with roughly 300,000–350,000 cumulative installations by 2019 [59,100]. The ambitious goal is to install 5.3 million systems by 2030 covering 10% of Japanese homes [100,101]. In Europe, the targets are less ambitious. The target is to install more than 2500 systems by 2021 and deploy 10,000 systems annually thereafter [102,103]. The state-of-the-art and future targets for m-CHP, 0.3–5 kW system, are summarized in Table S9 [41].

The South-Korean government has set a target of 100,000 m-CHP systems by 2020 [104]. In Japan, 93% of the systems installed are based on PEMFC technology. The systems have reached the target price of ¥800,000 (US$7350) per unit ($\leq$1 kW), and no more subsidies are given. The price for a SOFC system ($\leq$1 kW) is ¥1,230,000 (US$11,300). The micro-CHP systems use methane or LPG as a primary fuel, and a fuel processor is needed to produce H_2 to be fed to the FC module. No fuel processor is needed when H_2 is used as the primary fuel, which would simplify the micro-CHP system and decrease its cost. A micro-CHP system using green H_2 produced by wind power has been demonstrated in Lolland island, Denmark in collaboration with IRD fuel cells and local authorities [105]. A special case of the micro-CHP is an off-grid system where electrolytic H_2 is produced for on-site storage and reuse. Typically, such hybrid systems have been designed for residential applications (see Fig. 5), integrating photovoltaic panels for the production of electricity, short-term battery storage, electrolysis systems to provide the H_2 for long-term storage, and FCs to supply the electricity [106]. Although not economically feasible yet, commercialization efforts have started in Germany [107].

Backup power

Backup power (BUP) for telecom towers is another early niche market for PEMFC and DMFC [108]. The number of units supplied by different suppliers are listed in Table S10. The average system size is 5 kW like for the MHE. Larger units are supplied to data centers and hospitals. However, as they mostly use natural gas as the primary fuel, they are not further discussed here.

Prime power

A large FC system typically uses natural gas or biogas as the primary fuel. South-Korea is the leading market for MW-scale prime FC power. MCFC used to be the leading technology choice. However, phosphoric acid fuel cell (PAFC) and SOFC technologies are gaining ground, and the leading technology providers Doosan (PAFC) and Bloom Energy (SOFC) are showing increasing interest in pure H_2 as the fuel for their systems [59]. Industrial by-product H_2 from processes like dehydrogenation and chlorine production offers here a niche application. Apart from being produced for on-site industrial usage, it must be considered that H_2 is also produced as a side stream or by-product. A few pilot plants where by-product H_2 is used for electricity generation in a PEMFC stack are known. The installation at the Akzo Nobel chlor-alkali plant (Delfzijl, the Netherlands) is one of the most representative, with a 70 kW FC starting in 2007 and having over 30,000 h of operation [10]. A scale-up of the technology has been demonstrated with the 1 MW PEMFC power plant in service at the SolVin chlorine plant in Antwerp-Lillo (Belgium) since 2012, and later being transported to Martinique for further operation [109]. The world's first 2 MW PEMFC power plant (with combined heat and power) is already operating in a chlor-alkali plant (Ynnovate Sanzheng Fine Chemicals Co Ltd) in Yingkou, China [110]. Based on such examples, it is foreseen that many opportunities (and challenges) are available for the chemical industry, in terms of introducing large-scale production of renewable H_2.

H_2 combustion

H_2 is considered one of the most prominent fuels due to it being clean (no emissions of CO_X and soot) and its extremely high gravimetric energy density compared to fossil fuels. Due to its good flammability, H_2 can be employed as a combustion fuel in different types of burners, internal combustion engines, and turbines. The adiabatic flame temperature for H_2 (2045 °C) in comparison with acetylene (2400 °C), propane (1980 °C) and methane (1957 °C) in air, qualifies H_2 as an effective combustion fuel also for high-grade heat. A comparison of the combustion properties of H_2 with other fuels is provided in Table S11. In addition, the amount of energy liberated for H_2 combustion (LHV: 120 kJ g^{-1}) is ~2.5 times the heat of combustion of typical hydrocarbon fuels (gasoline (45 kJ g^{-1}), diesel (43 kJ g^{-1}), methane (50 kJ g^{-1}), propane (46 kJ g^{-1}), etc.). Hence, the H_2 mass required is ~ one third that of a typical hydrocarbon, for any specific load. However, the drawback of employing H_2 for combustion is due to the very low density of H_2 (i.e., the low volumetric energy density of

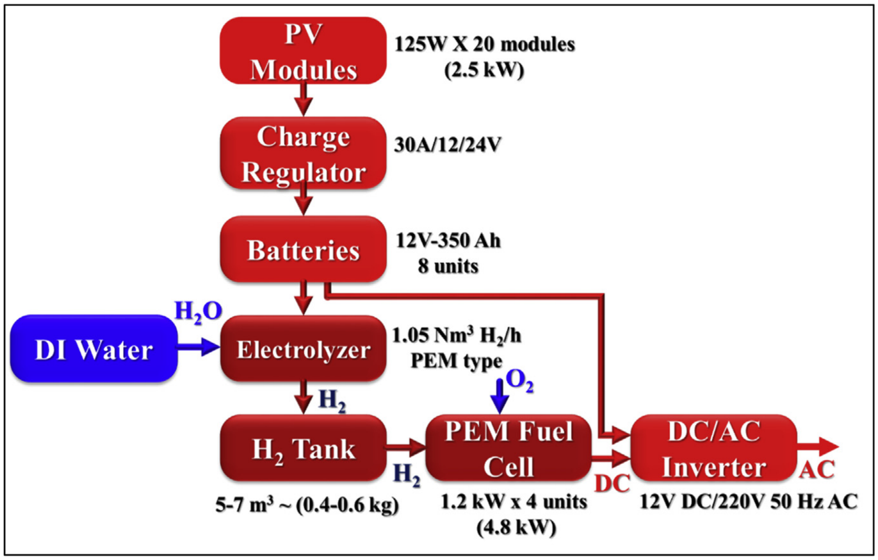

Fig. 5 – Hybrid system designed for residential applications.

~10 MJ m^{-3}) - an order of magnitude lower than that of the natural gas at STP, due to the very low molecular weight of H_2. The flashpoint of H_2 is also extremely low (<−253 °C) making it the most flammable among various fuels such as methane (−188 °C), propane (−104 °C), gasoline (−43 °C) and methanol (11 °C). In particular, 4–75% of H_2 is flammable in air and 15–59% is explosive at ambient temperature. The octane number, one of the key characteristics for combustion is also highly favorable for H_2 (130) compared to methane (125), propane (105), octane (100), gasoline (87) and diesel (30). This section reviews the status of the H_2 usage in an internal combustion engines (ICE), gas turbines, and other heating systems [111].

Internal combustion engines

H_2 internal combustion engine (H_2ICE) technology can be divided into port fuel injection (PFI) and direct injection (DI) methods using spark discharge or dual fuel operation with pilot diesel, respectively. In the spark ignition (SI) ICEs, PFI based engine combustion mode using H_2 will have pre-ignition, knock, and backfiring issues due to lower ignition energy and quenching distance of H_2, leading to lower power output along with efficiency degradation of engines. It has been demonstrated that the ignition energy of H_2-air mixtures at ambient pressure increases exponentially with a decreased stoichiometry, solving the pre-ignition issue [112]. In particular, turbocharging along with H_2 DI is proposed to solve the disadvantages of the H_2 PFI SI engine [113]. Several configurations such as liquid H_2 injection system, direct injection H_2, pressure-boosted H_2ICE or hybrid-electric H_2ICE have been explored for performance improvement and emission reduction. In particular, liquid H_2 can be used in the ICE (Fig. 6(a)) with the fuel transfer system for enhanced performance without any exhaust emissions [114,115]. High-pressure H_2 can also be directly injected into the cylinder through an injection nozzle with a controlled spread in the combustion chamber (Fig. 6(b) [116], avoiding the backfiring issue of PFI [117]. As shown in Fig. 6(c), H_2 pressure can be enhanced to obtain the maximum power density of H_2ICE [118]. Interestingly, high-pressure H_2 direct-injection operation based ICE performance can achieve similar efficiency as diesel engines, by optimizing injection pressure, duration, ignition timing, and injector orientation [119,120]. In a hybrid electric vehicle, the electric hybrid powertrain operates from electricity produced by H_2ICE with improved efficiency (Fig. 6(d)) [118]. A port-injected H_2 charge ignition can be triggered by pilot diesel fueled DI for improving the H_2 energy contribution up to 97% [121]. In addition, the preignition issue can also be excluded by reducing the exposure time of H_2 mixture to hot spots. The effects of H_2 use on gasoline, LPG, and diesel engines have been examined thoroughly in a very recent review and note that the gasoline engines are more favorable to benefit from H_2-enrichment [122]. However, the Belgian-British CMB. TECH prefers dual-fuel H_2-diesel engines for heavy-duty maritime, trucking, and rail applications [123].

Several concept cars were developed by automotive manufacturers in the decade of 2000–2010 (or more strictly, converted from previously existing gasoline engines). Probably the most well-known was the BMW H_2 7, with 100 units built from 2005 to 2007, and based on the BMW 7 Series (760Li) with a 6-Liter V-12 motor [114,124]. However, H_2-powered ICEs have been dropped by major automotive manufacturers around the world, in favor of FC vehicles. Current research is focused on H_2 addition to other fuels (diesel, gasoline, methanol, and NG) for improving performance and reducing emissions in ICEs [125,126].

Gas turbines

With the inherent fuel-flexibility of gas turbines (GT), H_2 or any other fuel can be employed by configuring the new system, or the existing ones using traditional fuel (e.g. natural gas) can be retrofitted, with a major focus on power plant decarbonization [127]. A schematic of GT in Fig. 7 shows the

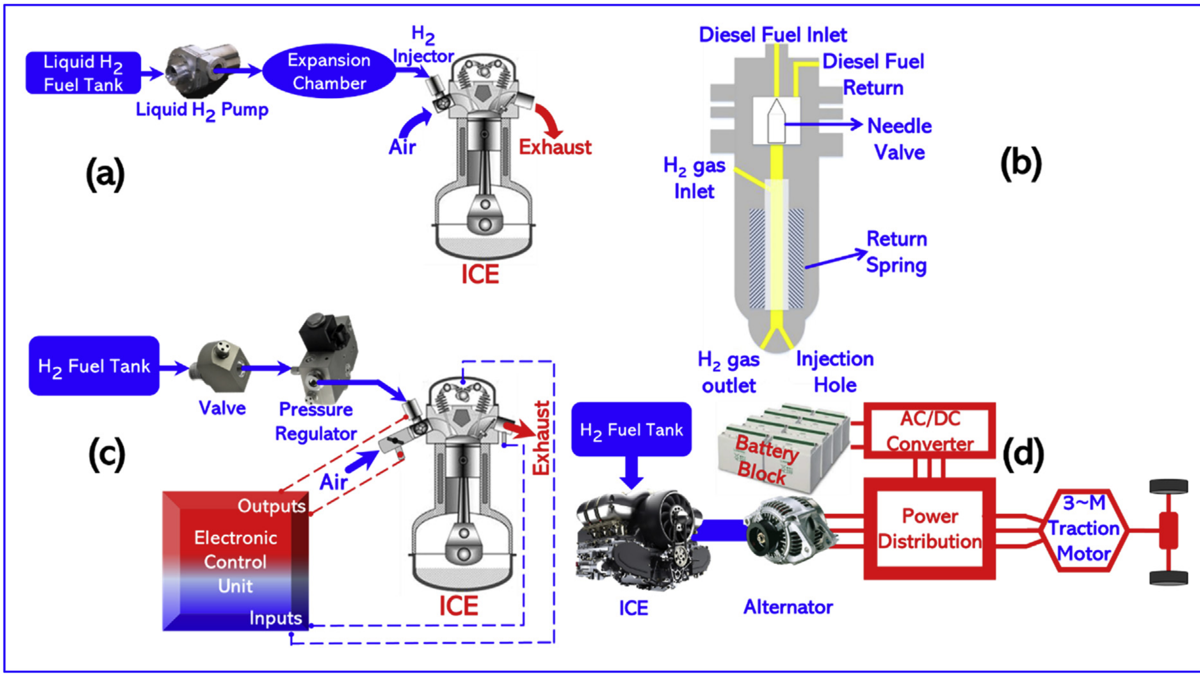

Fig. 6 – Schematic representation of (a) liquid H_2 storage and injection system, (b) injector used for DI-H_2ICE, (c) pressure-boosted H_2ICE, and (d) a hybrid-electric version of an H_2ICE [113].

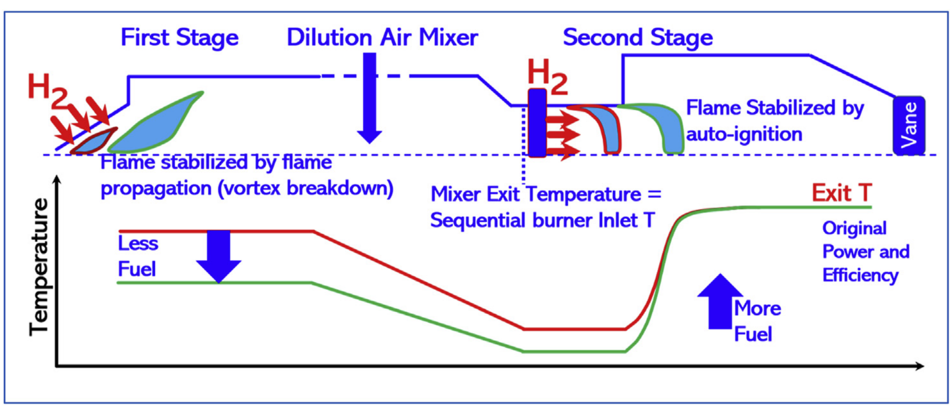

Fig. 7 – A schematic of a gas turbine showing fuel flexibility.

fuel flexibility with combustion occurring in both stages one and two at identical operating pressure.

In particular, the combustion properties of the H_2 fuel should be carefully considered to operate the system in a safe manner with required changes in the fuel accessories and the bottoming cycle components depending on the H_2 ratio [128]. There are several reports in evaluating the suitability of fuel mixtures like NH_3–H_2 blend (70–30 vol %) [129], natural gas - H_2 blend (90–10 vol %) [130], and methane - propane – H_2 blend (~50-20-30 vol %) [131] with a major goal to improve combustion stability and overall efficiency with a reduction in carbon and nitrogen oxide pollutants. Developmental efforts by Mitsubishi Hitachi Power Systems, GE Power, Siemens Energy, and Ansaldo Energia for employing 100% H_2-fueled gas turbines are the major shift towards a low carbon footprint, H_2 society, and in improving renewable energy mix ratio with a thrive in the H_2 economy [132].

Thermal energy

In addition to ICEs and GTs, H_2 can be burned for producing high-grade heat (water and space heating, and as cooking gas), as a zero-carbon alternative to natural gas. Heat-intensive industries such as aluminum, cement, petrochemicals, refining, iron, steel, and pulp and paper could benefit from the use of high-grade heat generated by burning green-H_2. Even though H_2 has a Wobbe index number of ~48 MJ/m^3, which is not too far from that of the natural gas (51 MJ/m^3), gas appliances designed to operate with natural gas cannot employ H_2 due to its extremely high combustion velocity (or flame speed). Hence, the existing burner heads should be replaced with custom designs for controlled combustion of H_2 [133]. Overall, the H_2 safety standards are in place for industrial applications with well understood physical and chemical characteristics of H_2 and several pilot burners have been developed [134,135]. However, the risks in using H_2 fuel for space heating in buildings are not fully known as the possibility for H_2 ignition within a building is certainly higher than that with natural gas. In addition, H_2 burns without any smell or color and there are no known odorants as of now. The safety of domestic H_2 boilers and stoves can be improved by catalytic combustion [136,137]. However, as these burners use Pt as the catalyst, it is adding to the cost of these appliances. For various thermal energy applications, H_2 can lead to decarbonization by blending with natural gas (Fig. 8) without major upgrades in the current grids for low H_2 concentrations [37], and the gas grid could be progressively upgraded to distribute pure H_2. The city of Leeds in the UK performs a feasibility study to convert a local gas network and all appliances to 100% H_2 (Fig. 8) [138].

Heating systems can also employ combined heat and power (CHP) technology based on high-temperature FCs (MCFC and SOFC) with established safety records, for various applications at different scales. In recent years, fuel cell CHP has been deployed in Asia but has not generally been highlighted in other regions in a large scale. As given in the web chart (Fig. 9), the running cost of H_2 is the minimum compared to all the currently employed fuels for generating thermal energy [139]. However, the higher capital cost for production and the lack of infrastructure for distribution make the H_2 deployment less feasible in the near term. In particular, green H_2 is a zero-carbon alternative to natural gas, as long as it is produced using renewable resources and delivered/dispensed through the existing gas grid network.

The market potential for green H_2

A 2015 study supported by the FCs and H_2 Joint Undertaking (FCH JU) on the commercialization of energy storage in Europe [140], identified Power to H_2 (P2H) as an energy option with no contribution in solving the power deficit, but with the potential to fully absorb the surplus from renewable energy sources [140]. It is concluded that by 2050 there will be economic viability for very large amounts (from today's 40–~400 GW in the EU) of Power-to-Power (P2P) storage for integrating intermittent renewable energy sources (RES) based systems. Even then, there may be large amounts of excess renewable energy, which could not be used directly or through P2P storage. However, producing H_2 using the excessive electricity by water electrolysis and use of this H_2 in the gas grid (P2G), mobility (P2H), or industry (P2Industry), contributes to the indirect electrification and decarbonization of these sectors. Installed electrolyzer capacity to be in hundreds of GWs in Europe by 2050, and several TWs globally. Key regulatory obstacles identified were (i) lack of clarity on the rules under which storage can access markets, (ii) application of final consumption fees to storage, and (iii) payments for curtailment to RES producers.

Further, the FCH JU supported a study in 2017 to identify profitable H_2 energy storage applications for Europe [141]. The analysis undertaken was at mesoscale, meaning detailed power system modelling by considering their expected grid reinforcements, with the goal to identify potential issues due to over-injection of RES in the network or by high local peak demand. The proximity to the natural gas network was also taken into consideration in identifying suitable locations. Moving to the monetization of P2H systems, different value streams were considered for industrial and transport applications to provide electricity grid services and lastly to inject H_2 into the gas grid. Three case studies were selected: a case of semi-centralized (SC) production for mobility application (1 MW scale), a light industry case (5 MW scale), and an oil refinery case (20 MW scale). The assumptions on performance and costs for alkaline and PEM electrolyser technologies were given for 2017 and 2025 for the three electrolyser capacities, as shown in Table 3. The profitability of a P2H project is determined by the H_2 selling price, the electricity cost (including grid fees, taxes, etc), and the system cost, as determined by the system size. Table 3 summarises the results of the analysis, where all business cases were profitable, with the exception of the refinery case in 2017. Payback time is reduced by up to 50%, when revenues from grid services and H_2 injection to the natural gas grid are taken into consideration – stacking up of revenues. To build a profitable business case, electricity price and H_2 gas grid injection tariff should not exceed 40–50 and 90 €/MWh, respectively.

In early 2020, H_2 Europe (Industry Grouping of the FCH JU) released a document on a "Green Hydrogen for a European Green Deal Initiative by 2030" [142]. The analysis calls for a 40 GW electrolyzer capacity to be installed in Europe, 6 GW captive market close to the demand locations, and 34 GW close to the resource. Similarly, another 40 GW of electrolyzer capacity can be installed in North Africa, with 7.5 GW for the domestic market and 32.5 GW of H_2 production capacity for

Fig. 8 – Comparison of (a) natural gas, (b) H_2 enriched natural gas, and (c) H_2 flames for thermal energy applications.

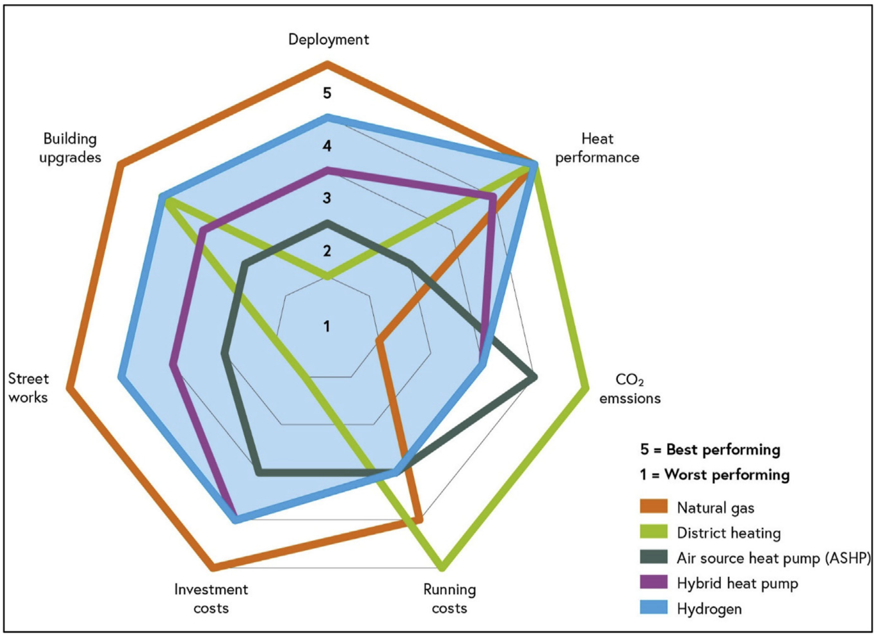

Fig. 9 – Comparison of natural gas and low-carbon heating technologies for large-scale retrofit deployment to domestic buildings.

Table 3 – Summary of profitability of three business cases in Europe [141].

Parameter	SC Mobility (Albi, France)		Light Industry (Trige, Denmark)		Large Industry (Lubeck, Germany)	
	2017	2025	2017	2025	2017	2025
Primary market H_2 (Ton/year)	270	950	900	900	3230	3230
Average total electricity price (€/MWh)	44	45	38	47	17	26
Nominal Size (MW)	2	12	6	6	40	40
CAPEX (1000*€/MW)	3600	1900	1760	1400	1480	960
H_2 cost (€/kg)	6.7	4.1	3.5	3.4	2.4	2.3
H_2 price (€/kg H_2)	7	6	5	5	1.8	2.6
Net margin per kg H_2 (€/kgH_2)	0.3	1.9	1.5	1.6	-0.6	0.3
Share of grid services in net margin (%)	75	72	39	37	-	85
Net margin without grid services (k€/MW/year)	39	71	228	248	-146	30
Net margin with grid services (k€/MW/year)	159	256	373	393	-13	195
Payback Period without grid services (years)	11	9	4.6	3.7	-	8.4
Payback Period with grid services (years)	8	4.5	3.4	2.7	-	3.5
Key risk factors	Taxes and Grid fees, H_2 price, Fleet Size, Injection tariff, etc.		Taxes and Grid fees, H_2 price, etc.		Taxes and Grid fees, Carbon price, etc.	

exporting H_2 to Europe using the existing natural gas pipeline network [142]. The total investments in electrolyzer capacity are estimated at € 25–30 billion, creating 140,000–170,000 jobs in manufacturing and maintaining 2 × 40 GW of electrolyzers, in Europe and Africa. The installation of this electrolyzer capacity along with the solar plants and wind parks for feeding them with green electricity would lead to 82 million tons of CO_2 reductions per year. The renewable H_2 cost would be competitive with low carbon H_2 (SMR + CCS) by 2025 at 1.5–2 €/kg and with grey H_2 (SMR) by 2030 at 1–1.5 €/kg. The global market potential by 2050 as estimated by IRENA, BNEF, Fraunhofer, and H_2 Council are 5280, 7380, 9000, and 21,700 TWh, corresponding to 134, 187, 228, and 549 million tons H_2, respectively [143]. The FCH JU has estimated € 430

Table 4 – Strategies adapted in decarbonizing transport and energy production sectors, by a few leading countries.

Countries	Major Activities
USA	California is aiming for 1000 H_2 fueling stations and one million FCEVs, by 2030.
Argentina	Signed an Agreement with Japan for producing green H_2 from wind power, in 2019.
Netherlands	Successfully tested a turbine using a blend of 30% H_2 and 70% natural gas and aims to employ 100% H_2, by 2025.
Austria	Operating world's largest green H_2 production plant, since 2019.
South Korea	Plans to build three H_2 powered cities by 2023 and powering 10% of the country's need through H_2, by 2030.
Japan	Leading the world in building H_2 Society with 100+ H_2 fueling stations.

billion, (with a necessary support of € 145 billion as a COVID-19 economic recovery plan for the efforts towards realizable H_2 economy) the total investment required to achieve the targets for transition towards H_2 economy up to 2030 [144]. These estimates form the base for the new EU H_2 strategy launched in July 2020 [145]. Such investments not only contribute to progress towards a clean energy system, but also would dramatically scale-up the H_2-related industry creating and securing highly-specialized jobs and economic growth.

The market for PEMFC is expected to grow at a compound annual growth rate (CAGR) of 15.28% during the period 2019–2024 [146]. The main reason is based on the improvements in R&D activities in this field, making PEMFC technology competitive with other alternatives, such as Li-ion batteries, leading to a greater penetration on the vehicle market. Nowadays, the cost of these technologies along with the lack of refueling infrastructure are some of the main barriers for their commercialization for stationary and transportation applications.

Several studies on system cost analysis for automotive FCs also show that the total system costs are approaching the DOE targets with over 100,000 units per year. Trucks and other heavy vehicles have been the main sector adopting FC technologies since 2017. The "Fuel Cell Industry Review" published yearly, showed in its 2019 report that a total yearly FC shipment exceeding 1 GW was achieved in 2019 for the first time [59]. An increasing trend is clearly observed as only 300 MW were shipped in 2015. A combination of new innovative technologies, government policies, and infrastructure is rapidly emerging as several countries (Table 4) prioritize green H_2 for their energy future and build the practicalities in establishing H_2 societies with widespread applications.

Challenges and opportunities

The realization of the H_2 economy depends on major challenges being solved but leads to great opportunities for business development and benefits for society. One of the main challenges is the need for a green H_2 generation, replacing the current main route for producing H_2 which is steam reforming of fuels such as natural gas, thus producing grey H_2. A decarbonized H_2 economy with zero-carbon footprint will require green sources of H_2 [147,148], such as water electrolysis coupled to renewable energy sources (PV and wind) or solar thermochemical H_2 production [149]. The technology for electrolysis is sufficiently developed to allow for its integration with renewables such as PV and wind, and several pilot and large-scale demonstration projects are in progress. Anyhow, a major scale-up from 10 to 100 MW units today to GW scale units is still needed to reach the TW level deployment targets by 2050. The cost of the technology is however still too high for such large scale deployment, although substantial cost reductions are expected in the near future [150,151]. The cost of H_2 production from renewable electricity could fall 30% by 2030 as a result of declining costs of renewables and the scaling up of H_2 production. The potential of H_2 to further foster the deployment and penetration of renewables such as solar PV and the wind is unquestionable when it comes to store surplus energy in situations with lower demands.

The need for large scale and safe H_2 storage methods with a high storage density is currently also a major challenge [147,152]. The H_2 economy will not be realizable without appropriate storage systems, which must be covering not only small scale storage intended for local usage and applications [153], but also large scale storage of H_2 including even seasonal storage. The storage of H_2 is linked to another subsequent challenge, which is finding efficient means for H_2 transportation and distribution to the point of use (end-users). Although there are initiatives on-going such as distribution along the natural gas grid [154] and transportation in H_2 carriers including organic hydrides, MOFs, or ammonia, a major challenge remains to make H_2 distribution work in a real-life scenario within the H_2 economy. The first MW-scale Power-to-Gas project was demonstrated at Falkenhagen (Germany) in 2013, in a demonstration project run by Uniper Energy Storage [154,155]. The plant aimed to store wind energy in the natural gas grid, generating around 360 Nm^3/h of H_2 through electrolysis, and feeding it into the gas grid. In the USA, a major initiative is in progress in Utah, with plans to store renewable H_2 to reach an impressive 1000 MW energy storage plant in a salt dome. The company MHPS Americas is planning to produce electricity by gas turbines run on natural gas and H_2 mixtures, significantly lowering carbon emissions. In a later stage, a transition to fully H_2-powered turbines would be developed.

Finally, the challenges associated with the efficient usage of H_2 are still to be solved. The final efficiency of the conversion of electricity to H_2 via electrolysis and the subsequent H_2 conversion to electricity in FC systems is still rather low. Further technology developments will be required to ensure that H_2 energy is efficiently used within the H_2 economy. This involves not only electrolysis and FC systems, but also any other zero carbon footprint systems based on H_2. Despite the high H_2 penetration potential in the medium and long terms, further technology developments are highly required as the transition towards the H_2 economy based on current technology would require significant costs [156]. In parallel to the technology development and demonstration, preparation for the hydrogen economy should become an integral part of the infrastructure planning comprising transmission and distribution networks and storage facilities. Harmonized regulations and transparent market rules should be established in order for the industry to commit for the long-term investments [145].

As a cross-cutting issue, the societal acceptance of a transition towards the H_2 economy and the H_2 society is also expected to be a significant challenge, depending on local traditions, culture, and technology acceptance [157–161]. The transition towards H_2 should be in line with customer convenience and preferences in order to avoid adoption difficulties. As an example, it is an advantage that H_2 can provide the same refueling speed and range as existing combustion-engine vehicles. Indeed, Human Sciences will need to be significantly considered for achieving deep decarbonization and deployment of H_2 technologies, as many issues are involved such as consumer behavior and lifestyle or market design and circular economy.

In most cases, however, the challenge itself is backing a subsequent opportunity. This is particularly true in the transition towards the H_2 economy, wherefrom a general point of view, the challenge of the transition is providing the opportunity to progressively developing an energy system towards the zero-carbon concept, lessening the current global warming issues (see as an example the "A Clean Planet for all" EU vision [162]). The technology development requirements and the technology commercialization is a major opportunity for new business development and growth, green H_2 production from renewables will change energy and fuel markets [163]. This leads to opportunities for the potential creation of millions of high-quality jobs worldwide, as much as 30 M jobs according to the H_2 Council.

The H_2 Council, launched at the World Economic Forum 2017 [164,165] believes that by 2030, H_2 will already be a significant energy carrier with several millions of H_2-powered vehicles and an increasingly expanding infrastructure. The Council believes that the H_2 sector has the potential to involve a financial weight similar to the current hydrocarbons industry, expecting to involve annual revenues worth around $2.5 trillion by 2050. There are interesting initiatives led both by governments and private companies aimed at fostering the H_2 economy, mostly starting from a local point of view. It is worth mentioning Masdar City in the United Arab Emirates, and countries such as Iceland, Norway, and Japan. The fully sustainable Masdar City, outside of Abu Dhabi, is intended to host up to 50,000 people and 1500 businesses related to green technologies, where the city is planned to fully rely on solar and other renewable energies aiming at achieving a zero-carbon footprint. The government of UAE is committed to further develop its green energy economy and has worked with major companies such as Air Liquide and Toyota to derive strategies to strengthen the H_2 industry. In 2019, a major solar-driven H_2 electrolysis facility was inaugurated in Dubai, which is the first in the Middle East and North Africa (MENA) region.

Japan is probably the world leader in the progression towards the H_2 economy, being significantly supported by the government and with the involvement of major companies. Japan's "Basic H_2 Strategy" [166] was released in December 2017 with a commitment to become the first H_2 society, by achieving cost parity of H_2 with traditional fossil fuel. The future H_2-based energy system of Japan, consistent with the layout shown in Fig. 3 of Part 1 of the H_2 economy review series [1], is depicted in the H_2 Strategy (Japan METI-Ministry of Economy, Trade and Industry) [166,167] and relies on large amounts of H_2 imports from locations within the "sun-belt" in Australia and other countries. Japan intends to start the importing of liquefied H_2 by 2030 and has recently revealed the world's first ship exclusively designed for H_2 transport [3]. This strategy results in major opportunities for business growth and companies such as Kawasaki Heavy Industries are getting significantly involved. Kawasaki has started the construction of pilot H_2 liquefaction facilities in Victoria State, Australia, worth $355 million, to ship H_2 to Japan and aims to start exporting trials by the end of 2020. According to Australia's CSIRO, technology costs for green H_2 production are starting to significantly fall, and thus green H_2 costs are approaching the cost of fossil fuels so that Australia can soon export renewable H_2 to Japan and South Korea.

Opportunities for the automotive industry are also opening as the H_2 economy develops. The FCEV Mirai was released in 2016 by Toyota, with several thousands of units sold in Japan and the USA, and the Hyundai Nexo was released in 2019 with also over 3000 units sold in one year. Other initiatives such as the one by South Korea also represents major opportunities for industry and business development, as the government intends to carry out a major investment plan to increase the number of FC vehicles to over 6 million by 2040, raising in

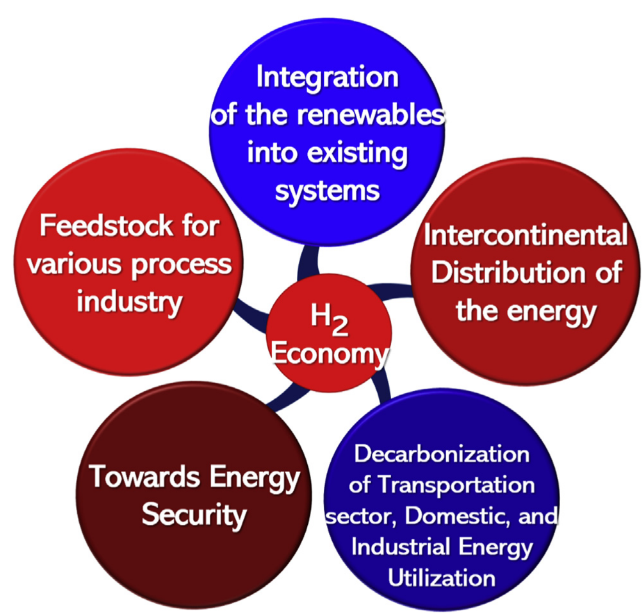

Fig. 10 – H_2 economy: Various opportunities.

parallel the H_2 refueling infrastructure up to 1200 stations. The government estimates a creation of over 400,000 jobs because of such measures and over $35 billion per year in value-added to the economy by 2040. The opportunities for the H_2 economy development in China are also huge. China is currently investing about 100 billion yuan per year in H_2 energy, and major Chinese vehicle manufacturers such as Great Wall Motors are about to release FC vehicles as early as 2022, with an overall estimated production capacity about 170,000 FCEVs per year. The opportunities for business growth and job creation are therefore enormous.

The IEA [6] highlights some near-term opportunities to widespread H_2 penetration in the energy system, such as making industrial ports key locations for scaling up the use of clean H_2. As described in Part 1 of this review series [1], a majority of H_2 is being produced by steam methane reforming for oil refineries and chemical industries concentrated in coastal regions in Europe, North America, and China. Encouraging these key players to progressively move towards greener H_2 production would result in the drive down of the overall costs, further boosting clean H_2 generation, for example by fueling trucks and ships and powering other nearby industrial facilities. Additional opportunities according to IEA [6] are to introduce clean H_2 in the already existing natural gas pipeline infrastructure (Power-to-Gas), boosting the demand for H_2 and thus reducing costs, or favoring H_2 in larger trucks, buses and trains for making the FC vehicles more competitive. Launching international shipping routes, as with the existing LNG market, would also contribute to the successful deployment of H_2 in the global energy system.

Fig. 10 illustrates various opportunities of the H_2 economy. Several industrial processes are using H_2 [168,169]. One of the most important sectors is the Chemical and Process Industry as discussed in Section Industrial uses of H2, which is the largest producer and consumer, H_2 is also widely used in the metallurgical industry as a reducing agent, for metal alloying, and the production of carbon steels and special metals. The semiconductor and electronics industry are also using H_2 as a reducing agent and as a carrier gas. The production of flat glass, where H_2 is used as an inert and protective gas, or as a coolant for generators are other examples of industrial uses of H_2.

In line with the Paris Agreement (2015), the intergovernmental panel on climate change (IPCC 2018) urges to reduce the GHG emissions by 45% by 2030 (compared to 2010) and then to net zero by 2050 [37,170,171]. In this massive transition, the H_2 economy will play a major role in achieving decarbonization [171]. As shown schematically in Fig. 11, grey H_2 production (current stage) from fossil resources is expected to be complemented with H_2 from biomass in the midterm as the share of production with renewables also increases, and the steam reforming of natural gas is coupled to CCS. Ultimately, green H_2 from renewable resources in the long-term will be achieving zero carbon footprint in all sectors. Apart from transportation and stationary applications, H_2 could also be used as a feedstock in various industrial processes for producing urea, steel, methanol, hydrocarbon and petroleum products etc., by transporting and distributing H_2 through pipelines, in the long term, as depicted in Fig. 11. The major barriers in the transition to H_2 economy are known to be economical, technical, implementation/execution compared to the existing well-established fossil fuel based technologies. However, sustainable nature of renewable resources for green H_2 production, large scale H_2 storage and transportation/distribution, and efficient and cleaner energy generation technology developments are projected to offset the limitation in the next few decades. The degree of involvement and support/incentives (such as ZEV credits for FCEV manufacturers) from governments and international stakeholders will determine how society progresses towards the H_2 economy.

Summary

The transition towards a green H_2 economy is still facing considerable challenges, where significant economic investments and technological developments are required to further progress towards a zero-carbon energy-based society. It is thus crucial to achieve international cooperation, in particular from policymakers and governments for establishing energy strategies to stimulate clean H_2 demand, support research, development, and demonstration, provide clear and harmonized regulatory requirements/standards, and support long-term investments through public-private partnerships, towards zero carbon footprints. The opportunities for economic growth, business, and job creation are in parallel extremely relevant, and needless to say, the enormous benefit for the global warming issues. According to the IEA “The Future of Hydrogen” report [6]: “clean H_2 is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. Now is the time to scale up technologies and bring down costs to allow H_2 technologies to become viable and sustainable for various applications”.

A very recent report [172,173] on the US H_2 economy road map organizes 4 key phases: 2020 to 2022, 2023 to 2025, 2026 to 2030, and post-2030, comprising policy enablers and H_2 supply and end-use equipment enablers with specific milestones for the widespread deployment of H_2 technologies.

As shown in Fig. 12, the goal is to establish decarbonization targets as guidelines for specific policy and regulatory actions, in the first two to three years. The next step is developing large-scale H_2 production through water electrolysis from renewables and steam methane reforming with CCS, for cost reduction by coordinating market participants and attracting investment, by 2025. During the 2026–2030 period, the major goal is to diversify beyond early adopter transportation and backup power segments and scale up infrastructure across the country. By 2030, the H_2 demand is projected to hit 17 million tons for various applications with ~1.2 million FCEV, 0.3 million material handling vehicles, and 4300 H_2 filling stations operating across the nation. H_2 is expected to be deployed at a large scale after 2030, across regions and industries with cost parity with fossil fuel alternatives, with a significant reduction in GHG emissions in industrial sectors and widespread decarbonization in buildings, and with a major share of zero-emission vehicles on the road. The growing H_2

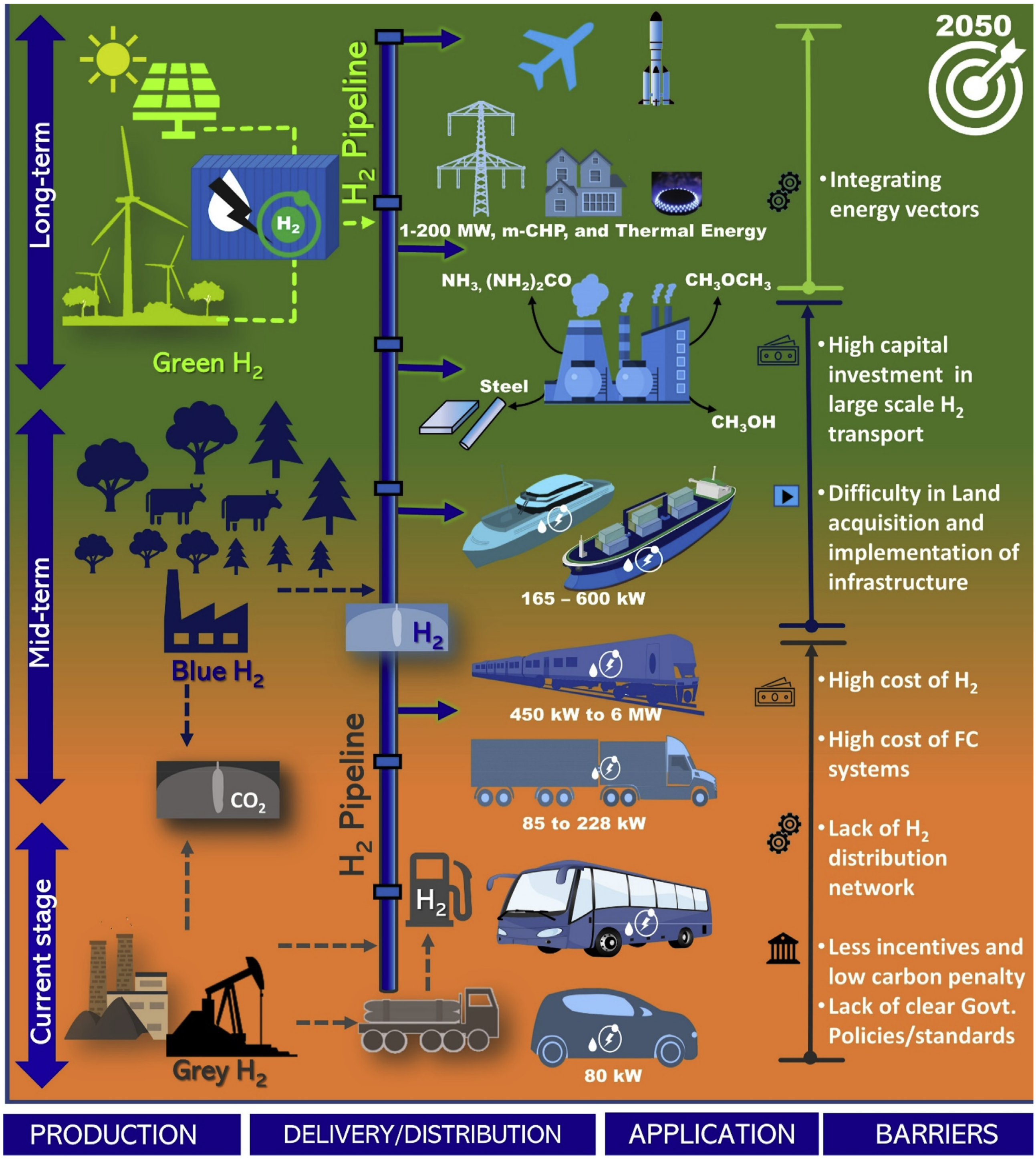

Fig. 11 – Transition from hydrocarbon to H_2 economy, related to H_2 production, transportation and utilization along with barriers.

industry is projected to create 700,000 jobs within the H_2 value chain, generating an annual revenue of ~$140 billion by 2030 and 3.4 million jobs and $750 billion per year by 2050. The total H_2 demand could reach 63 million tons for all the technologies including FCEVs, by 2050. The businesses functioning within the H_2 value chain are also expected to grow by technology exports to Europe, Japan, China, Australia, and Korea, as long as the policy enablers create incentives to attract private sectors for investing in and developing efficient H_2 technologies. Under these circumstances, H_2 economy is not futuristic but is realizable in the COVID-19 post-pandemic world through the next decade with necessary investments and support.

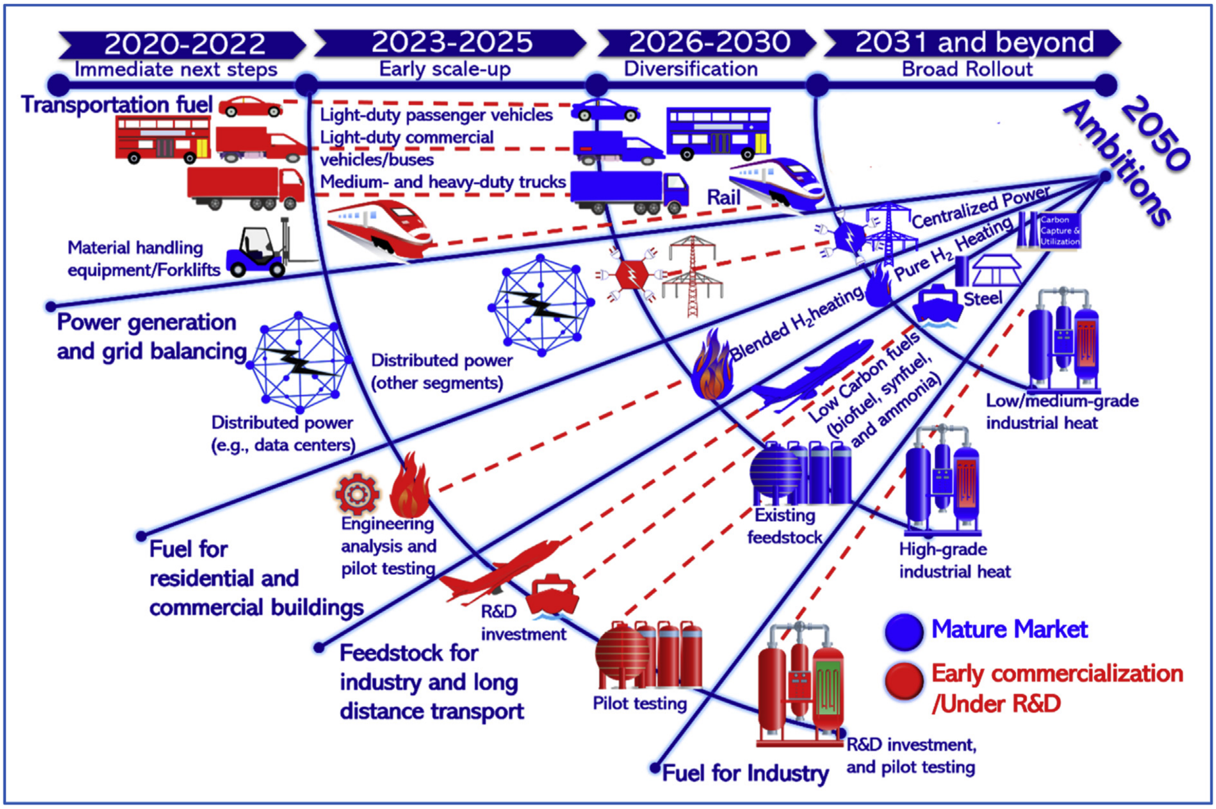

Fig. 12 – H_2 usage: realizable in the coming decades.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

AMK would like to thank The J. William Fulbright Foreign Scholarship Board and The Bureau of Educational and Cultural Affairs of the U.S. Department of State for the "Distinguished Chair Award" as well as Aalto University, Espoo, Finland for financial support.

Appendix A: Supplementary data

Supplementary data to this article can be found online at 10.1016/j.ijhydene.2020.07.256.

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