Power-to-fuel potential market

10

Daniele Candelaresi and Giuseppe Spazzafumo
Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, Italy

In the present chapter, a rough idea of the potential penetration of power to fuel in the market is tried to be given, from a perspective of complete replacement of fossil fuels with hydrogen and/or synthetic carbon-neutral fuels. Starting from an analysis of world energy consumption, the amounts of hydrogen, methane, methanol, dimethyl ether, ammonia, urea and formic acid necessary for a complete energy transition were calculated, with a focus on their application in various sectors, such as industrial, transport, building and electricity generation sectors.

Currently the energy market is still heavily reliant on fossil fuels. In 2017 the World Total Primary Energy Supply (TPES) amounted to 13972 Mtoe (million tonnes of oil equivalent). Of these, 27.1% was derived from coal, 32.6% from oil and 22.2% from natural gas (NG), for a total of 81.3% (equal to 11359.2 Mtoe) of energy demand met by fossil fuels (IEA, 2019a). The remaining part is supplied by nuclear (4.9%), hydroelectric (2.5%), biofuels and waste (9.5%) and other renewable sources such as geothermal, wind and solar (1.8%) (Fig. 10.1).

Renewable energy sources (RES) are growing strongly, but they still cover a minimal part of the global energy demand. This is linked both to intrinsic problems of renewable energy sources, already described in Chapter 1 (e.g. storage), and to the difficulty in the electrification of some end uses. By means of power-to-fuel it would therefore be possible to circumvent these obstacles, allowing the gradual, and potentially full, replacement of fossil fuels with renewable-based options. To make it clear how this replacement can be made, it is first necessary to understand how and where fossil fuels are used today.

To date, coal (world production: 3789 Mtoe) is mainly used in the energy transformation sector inside electricity plants or cogenerated heat and power (CHP) plants for power generation, but also in blast furnaces and coke ovens, while main final uses of coal in its form, known as Total Final Consumption (TFC), are in iron and steel production, nonmetallic minerals industry, chemical and petrochemical industry, other nonspecified industries and residential sector (IEA, 2019c). Main uses of coal are shown in Table 10.1.

Almost all crude oil production (4560 Mtoe) is used inside refineries to obtain oil products (world production: 4510 Mtoe). These oil products are mainly middle distillates (1403 Mt, million tonnes), motor gasoline (1006 Mt), fuel oil (434.7 Mt), LPG/ethane/naphtha (414 Mt), aviation fuels (314.6 Mt) and other products such as lubricants, white spirit, bitumen, paraffin waxes and others (567 Mt) (IEA, 2019a).

Power to Fuel. DOI: https://doi.org/10.1016/B978-0-12-822813-5.00009-6

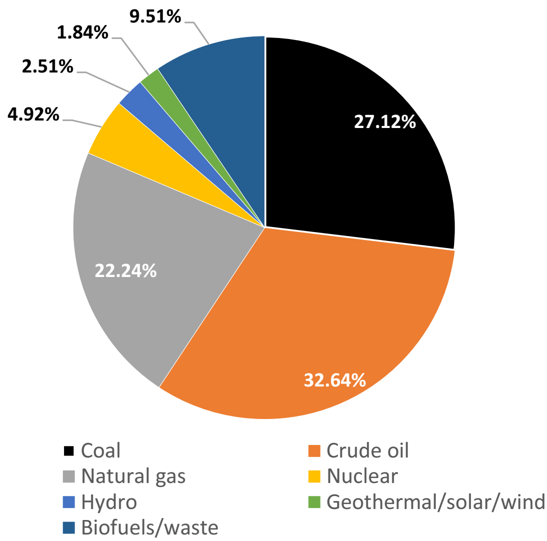

Figure 10.1 World total primary energy supply (TPES) in 2017.
Source: Data from IEA (2019a), Key World Energy Statistics, International Energy Agency. Paris: IEA. Available at: https://www.iea.org/reports/key-world-energy-statistics-2020.

Table 10.1 Main uses of coal.

	Mtoe	% (Coal TPES)	% (Coal TFC)
Energy transformation sector			
Electricity plants and CHP plants	2351	62.05%	-
Blast furnaces and coke ovens	282.2	7.45%	-
Others	135.8	3.58%	-
Total Energy transformation sector	*2769*	*73.08%*	-
Final uses			
Iron and steel production	313	8.26%	30.7%
Nonmetallic minerals industry	217	5.73%	21.3%
Chemical and petrochemical industry	108.46	2.86%	10.6%
Others nonspecified industries	77.25	2.03%	7.6%
Residential sector	75.55	2.00%	7.4%
Others	228.74	6.04%	22.4%
Coal Total Final Consumption	*1020*	*26.92%*	*100%*

TFC, Total final consumption; *TPES*, total primary energy supply.
Source: Data from IEA (2019c), World Energy Balances, International Energy Agency. Paris: IEA. Available at: https://www.iea.org/reports/world-energy-balances-overview.

In the energy transformation industry, oil products are used in relatively small amounts, mainly for energy industry's own use and in electricity plants, while almost all oil products that exit from refineries find employment in final consumptions within various sectors.

The largest share of oil products consumptions belongs to the transportation sector (2588 Mtoe), dominated by road transport and to a lesser extent by navigation and aviation. In addition to transport, not considering the nonenergy uses of oil, this is mainly consumed in the industrial (mainly chemical and petrochemical, nonmetallic minerals, construction, mining, and quarrying), residential, commercial and public services sectors and in the agricultural/forestry sector (IEA, 2019c). Main uses of oil derivatives, both in energy transformation sector and in final energy uses, are shown in Table 10.2.

Table 10.2 Main uses of oil derivatives.

	Mtoe	% (Oil TPES)	% (Oil TFC)
Energy transformation sector			
Energy industry own use	201.6	4.47%	-
Electricity plants and CHP plants	175.59[a]	3.89%	-
Others	162.63	3.61%	-
Total Energy transformation sector	*539.82*	*11.97%*	-
Final uses			
Road transport	1960.37	43.46%	49.38%
Navigation	271.35	6.02%	6.83%
Aviation	323.41	7.17%	8.15%
Rail	28.84	0.64%	0.73%
Nonenergy uses	633.51	14.05%	15.96%
Industrial sector	314.98	6.98%	7.93%
Residential sector	214.76	4.76%	5.40%
Commercial and public services sector	84.66	1.88%	2.13%
Agricultural/forestry sector	107.02	2.37%	2.69%
Others	31.28	0.69%	0.79%
Oil Total final consumption	*3970.18*	*88.03%*	*100%*

TFC, Total final consumption; *TPES*, total primary energy supply.
[a]Another 40.19 Mtoe from crude oil are used for electricity generation.
Source: Data from IEA (2019c), World Energy Balances, International Energy Agency. Paris: IEA. Available at: https://www.iea.org/reports/world-energy-balances-overview.

Table 10.3 Main natural gas (NG) uses.

	Mtoe	% (NG TPES)	% (NG TFC)
Energy transformation sector			
Electricity plants and CHP plants	1199.62	38.61%	-
Energy industry own use	290.77	9.36%	-
Heat plants	64.05	2.06%	-
Others	50.02	1.61%	-
Total Energy transformation sector	*1604.46*	*51.64%*	-
Final uses			
Industrial sector	567.60	18.27%	37.78%
Residential sector	440.58	14.18%	29.32%
Commercial and public services sector	190.31	6.13%	12.67%
Transport sector	104.71	3.37%	6.97%
Nonenergy uses	185.96	5.99%	12.38%
Others	13.17	0.42%	0.88%
Natural gas Total final consumption	*1502.34*	*48.36%*	*100%*

TFC, Total final consumption; *TPES*, total primary energy supply.
Data from IEA (2019c), World Energy Balances, International Energy Agency. Paris: IEA. Available at: https://www.iea.org/reports/world-energy-balances-overview.

World production of NG (3106.8 Mtoe) is consumed roughly half in the energy transformation industry (power plants and CHP plants, heat plants and energy industry's own use) and the other half as end uses in various sectors (Table 10.3).

With respect to TFC, NG is largely used in all industries, in residential sector, commercial and public services and finally in transport sector for road transportation and pipeline transport. The remaining part is for nonenergy uses (IEA, 2019c).

A first important opportunity for the power-to-fuel technique to penetrate the market would be its use to achieve the complete decarbonisation of the hydrogen currently produced, since hydrogen is already used in a variety of applications, especially industrial ones. The decarbonisation of currently used hydrogen would therefore allow, indirectly, a reduction in the carbon footprint of those products obtained from hydrogen. According to International Energy Agency (IEA, 2019b), the demand for hydrogen in the world is continuously growing: in 2018 it reached 70 million tonnes (Mt) in its pure form plus 45 Mt mixed with other gases. Hydrogen in its pure form is required mainly for specific applications such as refineries, ammonia production and use in fuel cells. Hydrogen mixed with other gases (e.g. in syngas), is mainly used in methanol production, in steel production in direct reduction of iron ore processes and other applications where it is required as a fuel or a feedstock. All this hydrogen is almost entirely produced from fossil fuels: 75% from NG (mainly by means of steam methane reforming) and 23% from coal (via coal gasification process), while electrolysis only accounts for 2% of today's global hydrogen production. Being produced from fossil fuels, this hydrogen is responsible for the annual emission of 830 Mt_{CO2}/year. If all the hydrogen required today was produced by electrolysis, using electricity from RES, many sectors could therefore be decarbonised such as the production of ammonia or, partially, refineries and methanol production. Producing all of today's dedicated hydrogen (70 Mt_{H2}) from electricity would result in an electricity demand of 3600 TWh, more than the total annual electricity generation of European Union (IEA, 2019b). In this sense it is possible to start having a first idea of the potential of power-to-fuel (115 Mt_{H2}/year), without taking into account the growth in demand expected in the coming years. In addition, electrolytic hydrogen could be used to produce other hydrogen-based substances, further increasing the range of possibilities. If one thought then, to replace each fossil fuel almost entirely with electrolytic hydrogen or synthetic carbo-neutral fuels, very important opportunities would appear. Present and potential uses of hydrogen and hydrogen-based chemicals will therefore be discussed below.

10.1 Industry

Hydrogen use today is dominated by industrial applications. In both pure and mixed forms, hydrogen is primarily used for oil refining (33%), ammonia production (27%), methanol production (11%), and steel production via direct reduction of iron ore (3%) (IEA, 2019b). Another future potential industrial use of hydrogen, currently still unexplored, would consist in generation of high-temperature heat.

10.1.1 Refineries

In refineries hydrogen is used as a feedstock, reagent or energy source, accounting for about 38 Mt_{H2}/year. This hydrogen demand is met for about one-third by on-site refineries by-products (e.g. from catalytic naphtha reforming), while about two-thirds are met by dedicated on-site production or merchant supply. Hydrogen in refineries is mainly used to remove impurities from crude oil, such as sulphur, and to upgrade heavier crude, through two processes: hydrotreatment and hydrocracking (IEA, 2019b).

Hydrotreatment is the process by which sulphur is removed, together with other impurities, by crude oil to obtain low-sulphur diesel fuel for instance, and to meet regulation standards regarding a variety of fuels. This process is often simply referred to as "desulphurisation" and it is largely hydrogen consuming. Due to growing concern about air quality, increasing regulatory pressure is expected to further reduce the sulphur content of fuels, thereby increasing the demand for hydrogen by refineries.

Hydrocracking is a process used to upgrade heavy residual oils into other oil products or lighter fractions, as they present a higher market value. Since the demand for heavy residual oil is decreasing while demand for light and middle distillate products is growing, the hydrogen need for hydrocracking is also growing. In addition, hydrogen is used by refineries for a variety of other minor processes such as upgrade of oil sands and hydrotreating of biofuels.

Under current trends, overall hydrogen demand in refineries is expected to grow by 7%, up to 41 Mt_{H2}/year in 2030 (IEA, 2019b). If an evolution in line with Paris Agreement is instead considered, the hydrogen demand by refineries would decline, as a consequence of oil demand decline. The replacement of this fossil-based hydrogen, with hydrogen produced by power-to-fuel would provide a potential early market for hydrogen from cleaner pathways, which could lower the emissions intensity of transport fuels.

In a long-term perspective, however, if all the oil used to produce fuels were replaced with hydrogen produced via electrolysis, about 3572 Mtoe/year coming from fossil fuels would be avoided, corresponding (with the same energy content) to a hydrogen production of 1246 Mt_{H2}/year.

10.1.2 Chemical sector

Power-to-fuel would represent an important opportunity to reduce levels of carbon emissions derived from the chemical sector since, also in this case, the vast majority of hydrogen required is produced from fossil fuels. The chemical sector output consists of a large variety of chemicals such as plastics, fertilisers, explosives and solvents. Anyway, seven primary chemicals can be considered: ammonia and methanol mostly, followed to a lesser extent by other "elementary bricks" used to obtain higher value chemicals, namely ethylene, propylene, benzene, toluene and xylene. These seven chemicals account roughly for around two-thirds of the chemical sector's energy consumption and feedstocks. In particular, ammonia production (175 Mt/year), which requires 31 Mt_{H2}/year, and methanol production (97 Mt/year), requiring 12 Mt_{H2}/year, represent the second and third hydrogen consuming sectors. In 2018, around 270 Mtoe/year of fossil fuels were used to produce the hydrogen needed for these two products, mainly from NG (IEA, 2019b). Only Asia-Pacific region, namely China, presents a large share of hydrogen production from coal.

A large part of ammonia (around 80%) is used for production of fertilisers such as urea and ammonium nitrate, while the remaining part is used for the manufacturing of explosives, synthetic fibres, pharmaceuticals and other chemicals for industrial applications (Market Research Future, 2020; Ye *et al.*, 2017).

On the other hand, methanol is used as a basis for the production of several other chemicals like dimethyl ether (DME), formic acid, formaldehyde, methyl methacrylate and various solvents (Grand View Research, 2019). In some regions, methanol also find application in the methanol-to-gasoline process. Two other processes, still in the demonstration phase, namely methanol-to-olefins and methanol-to-aromatics could increase the demand for methanol, for the production of plastics and other high added value chemicals (Tian *et al.*, 2015; Wang *et al.*, 2014).

Demand for hydrogen for ammonia and methanol production is set to increase from today's 44 MtH_2/year to 57 Mt_{H2}/year by 2030 and to 65 Mt_{H2}/year by 2050, without taking into account the possibility of their use as hydrogen carriers or as synthetic renewable fuels (IEA, 2019b).

Obviously, to completely de-fossilise ammonia and methanol production, it is not enough to de-fossilise only hydrogen production: considering the current demand level, ammonia would need also 144 Mt_{N2} with low environmental impact (e.g. separated from air using RES power), urea would need 112 Mt_{CO2} and methanol of around 133 Mt_{CO2} captured from air or from biogenic sources.

10.1.3 Iron and steel production

Direct reduction of iron-electric arc furnace (DRI-EAF) is a method for producing steel from iron ore, using a mixture of hydrogen and carbon monoxide as a reducing agent (Hsieh, 1979; Krüger *et al.*, 2020). This process today accounts for a hydrogen demand of 4 Mt_{H2}/year, corresponding to a 7% of the global primary steel production (1809 Mt of steel in 2018). Around 75% of this dedicated hydrogen production comes from NG, while the remaining 25% is derived from coal. Like other sectors, also the iron and steel sector produces hydrogen as a by-product, often in mixed form with other gases (e.g. coke oven gas). A part of this by-product hydrogen (9 Mt_{H2}/year) is internally consumed within the sector or burned inside blast furnace (basic oxygen furnace process) and another part (5 Mt_{H2}/year) is distributed for use in other sectors (IEA, 2019b).

Hydrogen produced via electrolysis could be therefore an interesting opportunity of decarbonisation for the existing steel production processes. Furthermore, in order to reduce steel production emissions, many efforts are being made to promote the development of novel production processes, still in the demonstration phase, consisting of a particular DRI-EAF that use only hydrogen as the key reducing agent. First commercial scale plants are expected for 2030 (HYBRIT Project, 2019). On a current trends basis, the global steel demand is set to increase by around 6% by 2030. Hydrogen demand from the iron and steel sector would increase from 4 to 8 Mt_{H2}/year by 2030, accordingly with the growth of the DRI-EAF process, from 7% to 14% of primary steel production. In the hypothesis of a 100% steel production by means of DRI-EAF process by 2050, hydrogen demand could theoretically reach 62 Mt_{H2}/year. In case the hydrogen breakthrough iron-making technology (HYBRIT) concept would satisfy 100% of primary steel demand by 2050, the hydrogen demand would instead potentially be equal to 67 Mt_{H2}/year (IEA, 2019b).

10.1.4 High-temperature heat generation

High temperature heat production for use in industrial applications could become another important source of hydrogen demand in the coming years, although there are currently no applications in this regard. In the industrial sector, heat is a utility required for a wide range of different processes, such as chemical reactions, gasification, drying, melting, etc. Heat can be used directly, as in a furnace or an oven, or indirectly by means of a hot fluid such as steam, air, pressurised-water and so on. The classification of heat for industrial uses is given on the basis of temperature ranges: low temperature ($<100°C$), medium temperature ($100°C-400°C$) and high temperature ($>400°C$). The current demand for high-temperature heat in industry is about 1280 Mtoe/year, of which 370 Mtoe/year (29%) are not consumed in the chemical and iron/steel sectors. Roughly half of this high-temperature heat (185 Mtoe) is consumed inside cement production plants. To date, almost all industrial high-temperature heat is derived from fossil fuels (around 65% from coal, 20% NG and 10% from oil). A small part of high-temperature heat is also produced by using biomass or waste. Electricity is widely used in industries to produce high-temperature heat, such as in the production of carbon fibre or in the electric arc furnaces, however electricity is often produced using fossil fuels. The level of demand for high-temperature heat is expected to grow, from 370 to about 400 Mtoe/year by 2030, which could potentially be provided by 130−140 Mt_{H2}/year (IEA, 2019b) or 335 Mt of renewable synthetic methane. Similarly, it is possible to calculate, with the same energy content, the amount of renewable synthetic fuels needed to satisfy the high-temperature heat demand.

10.2 Transport

Although in recent years there has been a rapid technological evolution to allow the electrification of some segments of the transport sector, fuels still remain a reliable option for the majority of transport modes. Potentially, all types of transport could be run on hydrogen or synthetic renewable fuels thus enabling emission reduction. In particular, hydrogen has been a subject of interest for many years as a potential clean transport fuel, since it can be produced from water and could emit only water as its main waste product, especially if is used in a fuel cell. Strictly speaking, when hydrogen is burned with air in internal combustion engines or turbines, it produces nitrogen oxides as a secondary emission with respect to water (Verhelst and Wallner, 2009). However, one of the main advantages of hydrogen is that it does not emit carbon in its direct use. For all applications in transport, hydrogen presents a main technical difficulty linked to the volume occupied: considering the energy content on a mass basis, hydrogen contains 120 MJ/kg (around three times more energy per kg than gasoline or diesel), but its energy content on a volume basis is very low, around 10.7 MJ/m^3 at standard conditions. Typically the storage pressures used for transport applications are 350 bar and 700 bar (energy density of about 4700−4900 MJ/m^3, but still around seven times lower than that of conventional fuels). To further increase the energy density, hydrogen can be stored in liquid form, but this requires large amounts of energy for liquefaction. Furthermore, many other technologies for efficient, safe and compact hydrogen storage are under study. In the meantime, the use of other renewable fuels produced through power-to-fuel could allow to circumvent this obstacle, using already consolidated technologies while reducing emissions at the same time. All synthetic fuels presented in this book have a certain range of potential applications in transport, in particular methane, methanol and dimethyl ether (DME) have direct uses also in internal combustion engines, while ammonia, urea and formic acid could primarily play a role as hydrogen carriers. Some of these fuels could also be used directly in specific fuel cells. In the following paragraphs the various possibilities will be analysed case by case. In addition to those considered in this book, there are a number of other liquid fuels suitable for specific applications (e.g. synthetic kerosene or jet fuel in aviation).

10.2.1 Cars

To date, very small amounts of hydrogen are used for automotive purposes, mostly in demonstration projects or, to a limited extent, in niche market present in some regions of the planet such as California, Japan and Germany. In 2018, approximately 11,200 hydrogen cars were on the road, with a growth of 56% compared to 2017, equal to 4000 new cars sold (IEA, 2019b). Although they have been growing rapidly in recent years, these numbers are still very small when compared to the stock of battery electric cars in the same year (5.1 million) and to that of global cars (more than 1 billion). In the automotive sector, hydrogen can be used in fuel cell electric vehicles (FCEVs) or in internal combustion engines (ICEs).

FCEVs have the advantage of having no tailpipe emissions (like battery electric vehicles) with exception for water, therefore they would reduce local air pollution and also global carbon dioxide emissions if ‘green hydrogen’ is used. Furthermore, fuel cells have an efficiency of about 55%−60%, more than double that the average efficiency of a conventional oil-fuelled ICE, drastically reducing fuel consumption. Due to their characteristics, proton exchange membrane fuel cells (PEMFC) type are mainly used in the automotive sector. When hydrogen is used in ICEs instead, tailpipe emissions mainly consists of water, variable amounts of nitrogen oxides (depending on the operating point of the engine) and very small amounts of carbon monoxide and particulate matter, resulting from the partial combustion of the lubricant oil. Also in this case a reduction in local air pollution would be obtained, if compared to that deriving from traditional gasoline or diesel vehicles. Furthermore, thanks to improved and faster combustion, the use of hydrogen increases the efficiency of the engine compared to a traditional vehicle, although not to the levels of efficiency obtainable with a fuel cell.

Another possibility, explored in the field of research, consists in the use of hydrogen mixtures with a traditional fuel (diesel, gasoline or NG) to feed an ICE. In this case, the advantage lies in reducing emissions and increasing efficiency, as hydrogen improves combustion characteristics. It also makes possible to use modest amounts of hydrogen, thus representing a possible temporary solution, while waiting for a greater diffusion of fuel cells.

Currently the energy demand for road transport amounts to 1960.4 Mtoe of oil plus 43.8 Mtoe of NG, and 60.7% of this demand comes from light-duty passenger vehicles (1216.5 Mtoe) (EIA, 2019; IEA, 2019c). Assuming an average efficiency of 25% for current vehicles, 55% for FCEVs and 40% for hydrogen ICE vehicles, if all cars currently on the road would be replaced with FCEVs, roughly 192 Mt_{H2}/year would be required, while hydrogen-powered ICE cars would require around 265 Mt_{H2}/year.

One of the main obstacles to the spread of hydrogen as a fuel for transport lies in the scarce diffusion of refuelling points. On the contrary, NG can count on an already very extensive distribution network, especially in some countries (Argentina, India, Italy, for example).

Renewable synthetic methane could replace the NG used today to power ICEs, referred to as compressed NG (CNG) vehicles. If all CNG used today for road transport (43.8 Mtoe including also buses and trucks) would be replaced by renewable methane (with the same efficiency as current vehicles), 36.67 Mt_{CH4}/year would be needed. Instead, to completely replace oil and gas used only from cars, and fuel the entire global car fleet with renewable methane, 1018 Mt_{CH4}/year would be needed. Similarly, renewable methanol (2821 Mt/year) and DME (1774 Mt/year) could also be used to feed ICEs, with characteristics similar to those of gasoline and diesel. In particular, DME is very suitable as a possible substitute for diesel fuel. Unfortunately, the calorific value of these two fuels is lower than that of traditional fuels: methanol has an energy content per kg equal to about 40% of that of gasoline, while DME has a lower heating value of 28.7 MJ/kg, equal to approximately 65% of that of diesel fuel. Finally, ammonia (2731 Mt/year) could also be used in ICEs, but due to the low flame propagation speed (5−13 cm/s), it is not optimal for use in automotive engines, however it may burn more rapidly if used in mixture with other fuels (Valera-Medina *et al*., 2018). Ammonia, urea and formic acid could instead be used as hydrogen carriers, even stored on board, releasing the hydrogen contained to be used for example in a hydrogen-powered fuel cell.

10.2.2 Trucks and buses

Regarding medium-duty and heavy-duty road transport, the same technologies already discussed for cars can be adopted. In this case, however, the power required by the propulsion system is greater, while there are less stringent limitations regarding the volume that can be occupied by the storage system.

In this sense, fuel cell electric buses and trucks can take advantage of large hydrogen tanks and use lower storage pressures, usually 350 bar. Compared to battery electric buses and trucks, fuel cell ones have faster refuelling times (a few minutes versus a few hours), greater autonomy (km that can be travelled between a refuelling and another) and less weight of the energy storage system. Also in this case one of the obstacles to the diffusion of these systems, lies in the lack of a capillary supply infrastructure.

Despite this, buses and trucks are seen as possible forerunners for the use of hydrogen, thanks to their mission characteristics: buses can refuel in their depot, run their public transport service for a certain time and then return back to the depot to refuel again. Therefore, by operating in hub-and-spoke missions, they can circumvent the problem of lack of refuelling points on the road. Trucks, on the other hand, are intended for long-distance journeys, especially long-haul trucks. They can therefore easily be used to reach two refuelling points even very far from each other without the need for intermediate refuelling, spending most of the time on highways, which could be more easily equipped with hydrogen fuelling stations.

As for cars, these vehicles can also use different technologies and alternative fuels. In some countries, CNG buses are quite common, and could easily run on renewable synthetic methane. The same applies to CNG trucks for logistical use, although less diffused. Higher-class trucks for heavier transports need monofuel CNG engines specially designed to meet the required power characteristics. IVECO and other companies are developing engines of this type and are carrying out research in the field of methane-hydrogen and diesel-hydrogen mixtures (IVECO, 2020; Vavra, Bortel, and Takats, 2019). Also in this case, renewable DME lends itself well, due to its characteristics, to replace diesel fuel (Towoju and Dare, 2017). Ammonia and urea are already commonly transported on-board on diesel trucks, albeit in small amounts, to ensure the proper functioning of the exhaust gas after-treatment systems, known as selective catalytic reduction (SCR). On a technological level, therefore, it would be quite simple to transport ammonia or urea as hydrogen carriers, to then use the latter inside hydrogen fuel cells.

The demand for energy from buses is equal to approximately 5.3% of the energy dedicated to road transport, or around 107.2 Mtoe, of which 104.9 Mtoe of oil and 2.3 Mtoe of NG (EIA, 2019; IEA, 2019c). Assuming an average efficiency of 25% for current engines, 55% for FCEVs and 40% for hydrogen-fuelled ICEs, buses could be powered alternatively by 17 Mt of hydrogen in fuel cells or 23.4 Mt of hydrogen in ICEs. Nevertheless, renewable methane (89.75 Mt), methanol (248.71 Mt), DME (156.42 Mt) or ammonia (240.71 Mt) in ICE could be used alternatively, assuming engines with the same efficiency as that of current vehicles ones.

Energy demand by trucks corresponds to 31.7% of the energy dedicated to road transport, or approximately 636 Mtoe (622 oil + 14 NG) (EIA, 2019; IEA, 2019c). Using the same assumptions made for buses, trucks could be powered alternatively by hydrogen in fuel cell (101 Mt), hydrogen in ICE (138.7 Mt), renewable methane (532.3 Mt), methanol (1475 Mt), DME (927.7 Mt) or ammonia (1427.6 Mt) in ICE.

10.2.3 Trains

Rail transport is already widely electrified in many countries. Anyway, hydrogen could be used to meet decarbonisation targets in nonelectrified railways. Today, nonelectrified lines are mostly served by diesel-powered trains. Some of these lines could easily be electrified, at low cost and with minor technical complications, while for other lines the electrification costs are very high or construction feasibility is technically challenging. In these situations, hydrogen fuel cell trains could take over, replacing diesel-powered trains. Some Alstom demonstration projects have already been launched in Germany, with Coradia iLint train, while some countries have already planned to purchase tens of hydrogen trains for the next few years, like UK, France, and recently also Italy with an agreement between Snam and Alstom (Global Railway Review, 2020; Snam, 2020). Hydrogen fuel cell trains could be competitive especially for long distance movement of large trains combined with a low-frequency network utilisation. These two conditions are quite common for rail freight. The energy demand from nonelectrified trains, therefore fuelled with petroleum-derived fuels, is equal to 28.84 Mtoe/year (EIA, 2019; IEA, 2019c), that using the same assumptions on efficiency described above, could be satisfied alternatively by 4.57 Mt_{H2} in hydrogen fuel cells, or by renewable methane (24.14 Mt), methanol (66.90 Mt), DME (42 Mt), or ammonia (64.7 Mt) in ICE.

10.2.4 Ships

Ships are typically powered by large and slow two-stroke diesel engines. In the naval sector, growing environmental concerns are slowly translating into regulatory pressures, in particular on the acceptable sulphur content in the diesel fuel burned and on emissions of nitrogen oxides and sulphur oxides. Nevertheless, the International Maritime Organization (IMO) has set the goal to reduce the total annual greenhouse gas emission by at least 50% by 2050 compared to 2008 and, eventually, fully eliminate harmful emissions (International Maritime Organization, 2018). Limitations on CO_2 emissions instead have been set via the energy efficiency design index adopted by IMO. To achieve these goals, the global maritime industry has begun to consider carbon-free and sulphur-free fuels such as hydrogen and ammonia, or carbo-neutral synthetic fuels such as renewable methane or renewable methanol.

The application of hydrogen fuel cells or electric batteries has been demonstrated on small ships used for shorter routes like ferries, but it still appears to be temporally distant for trans-oceangoing vessels (MAN Energy Solutions, 2019). Over the years, Man Energy Solutions has tested and developed various marine engines capable of using alternative fuels, including NG and liquefied natural gas (LNG), liquefied petroleum gas (LPG) propane and butane, ethane, ethanol, methanol, and finally ammonia.

Hydrogen in gaseous or liquid form would also be a suitable fuel for marine ICEs. Compressed gaseous hydrogen entails major problems regarding the volume occupied by storage tanks, with consequent loss of cargo, while liquid hydrogen (at −253°C) has a higher volumetric energy density but requires the use of cryogenic tanks. Liquid hydrogen ships could also be used for hydrogen imports and exports, consuming a small part of it for the propulsion of the ship itself. As already happens for LNG, liquid hydrogen would then need to be brought back in gaseous form once on land. For some boats and ships, the metal hydrides option is very interesting. They are very compact and very safe, but for mobile applications they have the drawback of being very heavy. However, this is not a drawback for boats and ships which have a fixed ballast to provide stability since metal hydride tanks can replace such a ballast.

Also ammonia is a very promising fuel for ships: it constitutes a quite good energy storage solution since it has a higher volumetric energy density than liquid hydrogen, but it is less expensive and complex to transport and store. Used as a fuel inside an ICE, it does not emit carbon or sulphur. In the case of marine engines, which are much slower than automotive ones, the ammonia flame propagation speed is sufficiently high (Dimitriou and Javaid, 2020). Moreover, ammonia can count on well-established production, management and storage methods, therefore has the potential to enter the market relatively quickly. If 'green ammonia' is used, it is also possible to strongly reduce the carbon footprint. Finally, ammonia transported by ship could act not only as a fuel but also as an efficient liquid hydrogen carrier for hydrogen imports/exports. Another important characteristic of ammonia is related to safety on board, because ammonia is much less explosive than hydrogen. Australia has recently launched a strategy that plans to export large amounts of green ammonia by ship to Japan and China, where it would then be converted into hydrogen (ANT Energy Solutions, 2013; Asian Rehub, 2020).

Starting from an energy demand from ships of 271.3 Mtoe (IEA, 2019c) and using the same assumptions on efficiencies described above, these could be powered alternatively by hydrogen in fuel cell (43.03 Mt), liquid or gaseous hydrogen in ICE (59.17 Mt), renewable methane (227.13 Mt), methanol (629.41 Mt), DME (395.85 Mt) or ammonia (609.2 Mt) in ICE.

10.2.5 Aviation

Decarbonisation is a major challenge for aviation. The aviation sector is responsible for the emission of about 900 Mt_{CO2}/year. Despite the fact that the efficiency improvement targets are set by the International Civil Aviation Organization (ICAO) at a growth of 2% per year (ICAO, 2018), emissions are expected to more than double by 2050. The Air Transport Action Group (ATAG) has set a goal of a 50% reduction in CO_2 emissions by 2050 compared to 2005 levels, while the European Union has set a more ambitious target of carbo-neutrality by the same year. In addition to carbon dioxide, aircraft also emit carbon monoxide, unburned hydrocarbons, nitrogen oxides, soot, and water vapour, which create contrails and cirrus clouds (McKinsey and Company, Clean Sky 2 JU and Fuel Cell and Hydrogen 2 JU, 2020). Given these targets, it is urgent to start implementing decarbonisation measures, even in the short-term.

To date, aircraft mostly use jet-fuel or jet-propellant, a fuel derived from kerosene, within aircraft turbines or piston-based engines. In some cases this can also be derived from – or mixed with – gasoline or naphtha, depending on the type of aircraft or engine. Although revolutionary electrically-propelled aircraft have been proposed, such as those powered by photovoltaic cells, fuel cells, or ultracapacitors, gas turbines will remain the most reliable and economically competitive option for many years. This is also because gas turbines have an excellent ratio between power output and weight, combined with the high energy density of liquid fuels, which allows aircraft to travel long distances. In this sense, large commercial aircraft, especially those used for longer journeys, seem to have few alternatives to liquid fuel, at least for the short and medium term. Moreover there are rigorous safety procedures, which imposes stringent quality standards on the characteristics of the propellant fuel used. Considering that aircraft are often refuelled in different states, and that some states could have different jet fuel quality, it is required that these technical fuel specifications are harmonised (ICAO, 2018).

To face environmental problems even in the near term, the aviation industry is developing alternative Sustainable Aviation Fuels (SAFs). These can be of the "drop-in" type, that is kerosene-like fuels, which can be distributed with the same infrastructure and can be burned in the same aviation turbines already in use without any adaptation, while allowing emissions to be reduced. Drop-in SAFs therefore, represent a quick substitute for conventional jet fuel, completely interchangeable or mixable with it, and can be used 'as is' on currently flying aircraft. On the contrary, any 'non drop-in' SAF would involve safety concerns and major adaptations. To meet these characteristics, a certain number of drop-in SAF have been developed in recent years. Among these, biofuels are very promising, such as Hydroprocessed Esters and Fatty Acids (HEFA) that can be produced from biomass or waste and other advanced biofuels producible from crops, algae, non-food biomass, municipal wastes, cooking oil and agricultural residues. Another important option is given by the so-called 'synfuels' or 'electrofuels' that use power combined with Fischer-Tropsch process to produce a liquid drop-in SAF similar to kerosene. By combining electrolytic H_2 produced from RES and CO_2 captured from a nonfossil source, a carbon-neutral drop-in fuel can therefore be obtained.

The global energy demand from aircrafts amounts to 323.4 Mtoe (IEA, 2019c). Through power-to-fuel technologies (with the same assumptions on efficiencies described above), aircrafts could be powered alternatively by hydrogen in fuel cell (51.29 Mt), hydrogen in turbine (70.52 Mt, better if liquid but also in gaseous form), or renewable methane (270.7 Mt), methanol (750.17 Mt), DME (471.80 Mt) or ammonia (726 Mt) in turbine. All these fuels are potentially exploitable to power aircraft, but not being 'drop-in' type fuels, they are among the new propulsion technologies.

The combustion of hydrogen inside aeronautical turbines (with low NO_x emission) is feasible, but requires the development of dedicated turbines still under study and the resolution of storage systems and refuelling problems. Assuming these technical developments, H_2 propulsion would be initially best suited for commuter, regional, short-range, and medium-range aircraft. Even long-range aircrafts could be powered by hydrogen, but they would be subject to major design changes and to the evaluation of economic convenience by 2050. Already in the early 2000s Airbus together with other airlines, universities and research centres explored the use of liquid hydrogen in aircrafts as part of the Cryoplane European project, while in recent years other projects involving hydrogen aircrafts financed by large private investors have begun to flourish (CNN, 2020; European Commission, 2002).

Finally, for all new propulsion technologies, the year of entry-into-service must be taken into consideration. Conventional aircraft development cycles occur about every 15−20 years until a new aircraft platform is introduced, while older fleets retire. For short-range aircraft, which make up the bulk of emissions, the next window of opportunity is expected to be around 2030−2035 (McKinsey and Company, Clean Sky 2 JU and Fuel Cell and Hydrogen 2 JU, 2020).

10.3 Buildings

The global buildings sector alone accounts for 2848 Mtoe, corresponding to about 30% of TFC. Of this energy demand (electricity included), 72.4% comes from the residential sector and 27.5% from commercial and public services. About 2200 Mtoe of this energy is dedicated to heat provision, such as space heating, hot water production and cooking. Roughly, half of this is produced directly from fossil fuels: NG accounts for 630 Mtoe, oil products for 299 Mtoe and coal for 109 Mtoe (IEA, 2019b, 2019c). Most of the remaining heat production in buildings is met by electrical equipment as electric resistance radiators and induction cook-stoves, heat pumps but also by district heating. To date, this energy is also produced mostly (85%) from fossil fuels, even if indirectly. Besides, solid biomass for heating purposes is still very significant in developing countries. Overall, the buildings sector is responsible for a 28% of global CO_2 emissions related to energy uses.

With respect to heat provision, buildings present two main challenges, namely the reduction of heat demand (by improving the energy class of buildings, plants and equipment) and the decarbonisation of emissions connected to heat production. In addition to heat pumps, many alternative technologies such as geothermal energy or solar thermal have been proposed, but their diffusion depends on many factors in the case of buildings: location and type of building, ownership, customer preferences, perceived comfort, reliability, capital and operating costs, etc. It is therefore very likely that various technologies will coexist in the future. In this scenario, power-to-fuel offers many possibilities for decarbonisation, both in the near and in the long term. The first that can come to mind is the partial or total replacement of NG with renewable synthetic methane. This would make possible to continue to use the already existing distribution infrastructure as well as existing devices such as NG boilers. Also hydrogen arises as a suitable decarbonisation solution both in the near term, through injections in small amounts in the NG pipelines, and in the long term in a dedicated 100% hydrogen infrastructure.

10.3.1 Renewable methane

To date, the global methane distribution network can count on a large extension of approximately 3 million km of pipelines, to which are added an enormous underground storage capacity and international trade of LNG transported by ship. The global demand for NG today (already presented in paragraph 10.1) is approximately 3900 billion m^3, corresponding to 3106.8 Mtoe (IEA, 2019c). Replacing all this NG with biomethane would be impossible due to concerns about land use change and competition of energy with food crops. Even considering replacing with biomethane only the 630 Mtoe of NG used for heating buildings, it would mean facing a 90-fold increase in biomethane production in the European Union and a 20-fold increase with respect to current world production (IEA, 2019b). Power-to-methane could overcome these limitations by producing renewable synthetic methane. Compared to hydrogen, the disadvantage consists in a lower production efficiency and a higher cost, associated with the additional methanation process. This could probably lead to an increase in gas prices for final consumers, if compared to NG. Regarding the production of heat in buildings alone, power-to-methane could replace the 630 Mtoe of NG used today with 527 Mt_{CH4} of synthetic renewable methane, while the replacement of all fossil fuels used for direct heat provision in buildings (1038 Mtoe) would need 868 Mt_{CH4}.

10.3.2 Hydrogen use in buildings

Currently, hydrogen is not used in the buildings sector, except for some demonstration projects, which are trying to explore different possible future uses of the fuel. Some of these projects are experimenting hydrogen blending in the NG pipelines, other projects instead involve supply of pure hydrogen to various devices such as hydrogen boilers, fuel cells or burners. The current largest project regarding 100% hydrogen supply via dedicated hydrogen pipeline to buildings is the H21 North of England (H21, 2018). This project also demonstrated the feasibility of reusing the existing (polyethylene) pipeline network and it is testing hydrogen boilers. In addition, the largest demonstration projects concerning stationary fuel cells for residential and commercial buildings and cogeneration for residential use are ene.field in Europe and ENE-FARM in Japan (Nagashima, 2018; Nielsen and Prag, 2017). In the Japanese project, developed since 2009 by a consortium that includes Panasonic and other major energy suppliers/fuel cell manufacturers, NG or LPG are reformed locally to produce hydrogen to feed fuel cells, thus bypassing the problem of hydrogen distribution up to the building. In addition to generating electricity, hot water is also produced for domestic use, achieving a total declared energy efficiency of 97% (ENE-FARM, 2020). Regarding numbers of units, around 300,000 should be in operation by the end of 2020, while 5.3 million units are expected by 2050 (Nagashima, 2018). In Europe, on the other hand, more than 1000 micro-CHP units have been installed around 11 countries and an increase to 2800 units is expected in the coming years.

Coming to a future perspective, a multitude of factors, including population density and energy class of buildings, could influence the future demand for hydrogen by this sector. For example, condominiums, multi-family buildings and large commercial buildings represent good opportunities for the use of hydrogen. In the second case, buildings older than 25 years (the majority of buildings in Europe and United States) represent an energy-intensive market share that will continue to demand a large amount of heat for many years to come, that could be satisfied by hydrogen. A complete electrification of consumption by means of electric heat pumps is not adequate for these buildings: unless major improvements are made in building energy efficiency at the same time, it could lead to large seasonal imbalances in the demand for electricity. Anyway, there are many opportunities for hydrogen use in buildings, which can be classified into two main categories: hydrogen blending in existing NG network and direct use of pure hydrogen for heat (and/or electricity) production in buildings. A third option regards indirect use of hydrogen to heat or cool buildings by using centralised systems in neighbourhoods.

10.3.2.1 Blending

Thanks to the possibility of injecting hydrogen into existing NG distribution infrastructure, it would be possible to delay the significant investment in a dedicated hydrogen distribution network later in time, focusing first on increasing the production of hydrogen from RES. It is also possible to vary the mixing percentages and this would ensure a gradual energy transition as well as a progressive reduction in CO_2 emissions. At the same time, this possibility has some disadvantages. First of all an obstacle to be overcome consists in the harmonisation of the regulations regarding the percentage of hydrogen admissible within the gas network, not only at national level but also at the border level. Secondly, a hydrogen injection could lead to an increase in the cost of NG for consumers, which must be carefully evaluated.

Another problem is linked to the lower calorific value of hydrogen per unit of volume compared to NG. The main concerns would be a reduction in the ability to transport energy by pipelines, the need for consumers to use larger volumes to meet an energy requirement, the adjustment of energy metering by gas meters and gas supply for some industries. Finally, there are technical limitations on the percentage of hydrogen admissible in a mixture with NG. The upper limit of this amount is mainly dictated by the various users or equipment connected to the network, in particular by those with a lower tolerance level.

Some existing components already have a high hydrogen tolerance without any need for upgrades, for instance many European gas heating and cooking appliances can tolerate up to 23% hydrogen. The Ameland project, in the Netherlands, tested successfully some equipment for heat provision in buildings such as boilers, gas hobs and cooking appliances (Kippers *et al*., 2011) with hydrogen mixtures with natural gas until 20%. In some cases, no problems were found until 30%. Other elements of the network such as gas meters and distribution and transmission networks also appear to have high levels of tolerance to hydrogen. Generally speaking, the most problematic elements from this point of view are compressors (10%), engines (5%), turbines (2%−5%) and some type of CNG tanks (2%), but in many cases it is possible to overcome these limitations with minor modifications which allow to increase their tolerance, for example, by changing seals in gas turbines (Altfeld 7 Pinchbeck, 2013; IEA, 2019b). These limit values are derived from legislative and/or technical limitations designed for generic cases, but there are components designed specifically for individual specific applications that can easily exceed them (e.g. some stationary ICE).

According to International Energy Agency, considering that the current demand for NG in terms of volume is equal to 3900 billion m^3, a replacement of 3% of this

NG with an equal volume of hydrogen would need about 12 Mt_{H2}/year (IEA, 2019b). However, this approach would lead to a reduction in the energy delivered by gas. Instead, if a replacement of the energy that was originally supplied by NG with an equivalent amount of energy supplied by hydrogen is considered, a 3% hydrogen blending would require around 31.8 Mt_{H2}. Both of these numbers are very significant and could lead to a major boost to the diffusion of hydrogen, creating an economy of scale for electrolysers. Similarly, considering the possibility of increasing the hydrogen percentage at a later time, a 20% hydrogen blending in current global uses of natural gas would need 69 Mt_{H2} for a replacement for the same volume and 212 Mt_{H2} for a replacement for the same energy delivered. Considering only the natural gas used in buildings for the supply of heat, and a substitution approach for the same energy delivered, a 3% hydrogen blending would bring about 6 Mt_{H2} in the final consumption of the buildings. Similarly a 20% hydrogen mixture would be equivalent to over 39 Mt_{H2} consumed in buildings.

10.3.2.2 Pure hydrogen

From a longer term perspective, if a dedicated 100% hydrogen distribution network were developed, it would be possible to meet the energy demand of buildings in different ways. Hydrogen boilers could provide the thermal energy necessary for space heating of buildings and for the production of hot water, without any CO_2 emissions. Another option is the cogeneration of heat and electricity using stationary fuel cells, as already seen for the ene.field and ENE-FARM projects. Finally, heating, cooling and electricity demand of buildings could be met by sending hydrogen to local district power plants for the cogeneration of electricity and heat and distribution of hot or cold flows through district energy networks. Potentially if hydrogen became cost competitive, it could replace all the NG dedicated to the production of heat for buildings with 220 Mt_{H2}, while to replace all the heat for buildings generated directly from fossil fuels would take 362 Mt_{H2}.

10.4 Power generation

In 2017, 25,606 TWh of electricity were generated: 21,605 TWh came from electricity plants and 4001 TWh from CHP plants. With respect to the total, 38.52% of electricity was generated from coal, around 3.29% from oil, 22.97% from NG, and 10.29% from nuclear power. The production of hydroelectric energy is equal to 15.94% of the total, while other renewables, albeit in strong growth, still play a rather marginal role: geothermal, wind and solar account globally for 6.64% and biofuels and waste for 2.33% (IEA, 2019a, 2019c). Fossil sources together to a total of 64.78%. Regarding the amount of primary energy from fossil sources used to generate this electricity, 2351 Mtoe of coal, 215 Mtoe of oil and 1200 Mtoe of NG were used (see Tables 10.1−10.3). It could be thought of directly replacing electricity generated from fossil sources with electricity generated from RES, however the nonprogrammability of RES constitutes an obstacle to their greater exploitation. To increase the possibilities of RES exploitation, an energy storage system is needed to decouple production from demand. One of the possibilities is to produce a synthetic fuel, easier to store, and then reconvert it in electricity when needed. This technique is known as power-to-power. Although this double conversion has significant efficiency losses, to date it represents one of the few viable and reliable alternatives to store energy on a large scale and for long periods (e.g. seasonal storage).

All the synthetic fuels presented in previous chapters offer various opportunities for decarbonising the electricity generation sector. In general, the greater the number of conversion steps, the greater the energy losses and the reduction in efficiency. From this point of view, hydrogen would be the most advantageous solution; however the possibility of using existing distribution infrastructures and more or less consolidated technologies, also increases the interest in more complex fuels such as synthetic methane and ammonia. Taking methane as an example, which is already one of the most widespread energy sources, it could be possible to replace NG burned today in power generation plants (1200 Mtoe), with 1004 Mt of renewable synthetic methane without making any change to the existing plants. If electricity generation from coal and oil were also totally replaced by synthetic methane, 1968 Mt_{CH4} and 180 Mt_{CH4} would be needed respectively, for a total of 3152 Mt_{CH4} to obtain a complete defossilisation of this sector using already proven technologies.

To date, hydrogen is not used for the generation of electricity, except in very few industrial sites where it is recovered as a waste product from nearby petrochemical or steel industries and then burned in a gas turbine to produce electricity, or in a few small-scale demonstration plants such as power plants with stationary fuel cells. For example, near Venice in Italy, inside the “Andrea Palladio” ENEL power plant, a 12 MW combined-cycle gas turbine fuelled with hydrogen is installed (Balestri *et al*., 2007; ENEL, 2009). This turbine uses hydrogen recovered from the nearby petrochemical complex EniChem of Porto Marghera. In particular, the hydrogen comes from the unaccumulable surplus produced by the chloralkali process and emissions for 17,000 t_{CO2}/year are avoided thanks to this turbine. In other cases, however, the hydrogen recovered from nearby industrial sites is not in pure form, but mixed with other gases and is burned in internal combustion engines to produce electricity (and heat). Some of these stationary engines can tolerate hydrogen-rich gases up to $70\%_{vol.}$ today, while future gas engines could run even on 100% H_2 (Herdin *et al*., 2007). Even some gas turbines can already burn mixtures containing high percentages of hydrogen, such as a 40 MW turbine installed in Korea, near a refinery, that was fuelled with a gaseous mixture containing up to 95% hydrogen for the past 20 years (Moliere, 1999). Finally, another application of hydrogen for electricity (and eventually heat) generation, today mostly at demonstration and small-scale, is in power plants with stationary fuel cells. The installed power worldwide to date is equivalent to 1.6 GW of stationary fuel cells or 363,000 units, anyway only 70 MW of these are fuelled directly with green hydrogen, while the majority uses NG reformed locally to obtain hydrogen to be used in fuel cells. Very few solid oxide fuel cells, currently mostly in demonstration projects, directly use NG as a fuel. Numerically, most of these fuel cells belong to the ENE-FARM project and can be classified as micro-cogeneration systems rather than as power plants, while few high-powered units, between 100 kW and 2.4 MW are around the world, such as in Japan, Korea and United States (Leo and Fuel Cell Energy, 2016; Toshiba, 2017). These high-power units can be combined in a modular way to create power plants, such as a 50 MW fuel cell power plant under construction in Korea (FuelCellsWorks, 2019). In addition to traditional power plants and distributed generation, other possible interesting applications for the generation of electricity using fuel cells consist of the supply of electricity in those situations where one cannot rely on the grid, namely portable generators, uninterruptible power supplies and off-grid power solutions. Ammonia is another promising synthetic fuel for power generation, as it can be used either as a hydrogen carrier or as an actual fuel, alone or in combination with other fuels, in a boiler, a turbine, an internal combustion engine or even in a fuel cell.

10.4.1 Renewable synthetic fuels in power generation

Many fossil fuel plants currently already in operation will remain so for many years to come. In this sense, it is essential to find a way to reduce as much as possible their emissions. Most of the synthetic fuels already present can be used in combination with traditional fuels in existing power plants with only minor plant changes.

For instance, hydrogen could be co-fired together with coal, oil or NG in a traditional boiler for steam generation, or blended with NG in different percentages and burned in a gas turbine. This technique is known as dual fuel combustion. The reduction of emissions in this case would be greater than the simple reduction due to the replacement of a part of fossil fuel, as the addition of hydrogen improves the characteristics and completeness of combustion. Similarly, hydrogen can also be mixed with oil or gas in internal combustion engines for stationary generation, as already discussed for engines for transport applications. Another option consists of the so-called attached-cycles: in this case hydrogen is not co-fired with the fossil fuel, but is burned with oxygen in a mixing superheater, to superheat the evolving fluid from within the fluid itself (Spazzafumo, 2003). The oxy-combustion of hydrogen in fact generates only water vapour and heat. Taking a traditional coal-fired steam plant as an example, it is possible to replace the traditional superheater with a mixing superheater of this type. On the one hand, this simplifies the plant layout, avoiding the necessity to return to the boiler to re-heat the steam, on the other hand it makes possible to reach much higher superheating temperatures, thus improving plant efficiency and performance with respect to a traditional steam plant.

Given its high hydrogen content, ammonia can also play similar roles like hydrogen and can be used as an energy storage and then decomposed to obtain hydrogen, or directly as ammonia in combination with fossil fuels. In this sense, the co-combustion of ammonia with coal seems very promising, since ammonia is currently cheaper and easier to store and manage than hydrogen. In 2017, an electric company in Japan (Chugoku Electric) has demonstrated with success to be able to burn ammonia together with coal at one of its coal plants of 120 MW power. The ammonia content used in the demonstration is 1% in terms of total energy content of the two fuels (IEA, 2019b; Muraki, 2018). Furthermore, IHI has also demonstrated in 2018, in another 10 MW combustion facility in Japan, that it is possible to increase the ammonia content mixed with coal up to 20% in energy terms (Power Magazine, 2020). In particular, the success of the experiment lies in the fact that there was no leak of unburned ammonia in the exhaust gases and that only minor changes are required to the traditional coal plant. According to the IEA estimates, if 20% of ammonia mixed with coal were used in all coal-fired power plants in the world by 2030, an ammonia demand of 670 Mt/year would be created, and this would require 120 Mt_{H2}/year to produce ammonia. The use of green ammonia together with coal could avoid the emission of a considerable amount of CO_2 into the atmosphere, around 1.2 Gt_{CO2}/year according to IEA estimates. The reduction in carbon emissions is accompanied by another side of the coin. Since ammonia contains nitrogen, its use as a fuel also lead to the formation of fuel-NO_x, causing concerns about the rise in total NO_x emissions. However, the 10 MW demonstration plant managed to keep these emissions within the usual limits and prevent unburned ammonia from escaping into the exhaust gases.

Regarding electricity generation based 100% on renewable synthetic fuels, there are still some technical challenges that make this option more likely for a medium-long term time horizon. Most of the gas turbines used today are already able to accept hydrogen levels from 3% to 5%, some can accept up to 30%, while in other cases percentages close to 100% can be reached depending on the design of the turbine (Goldmeer, 2018; Mitsubishi Power, 2019). Standard turbines capable of being fuelled entirely with hydrogen are expected by 2030 (Ditaranto, Heggset, and Berstad, 2020; EUTurbines, 2019).

Ammonia direct combustion in gas turbines has been already demonstrated in some micro gas turbines (powers lower than 300 kW) (Shiozawa, 2019), while larger gas turbines ($>$ 2 MW power) present some technical hurdles that researchers are trying to solve, such as flame stability and speed or containment of nitrogen oxide emissions (Valera-Medina *et al*., 2018). In addition to the direct combustion of ammonia, it is also possible to use it just as a long-term storage and to decompose it to obtain nitrogen and hydrogen, to burn only the latter in a gas turbine (van Wijk and Noordelijke Innovation Board, 2017).

Assuming a scenario in which hydrogen would replace fossil fuels to feed current power plants and an efficiency of 50% for a hydrogen plant, it would take 353 Mt_{H2} to completely replace only NG and 643 Mt_{H2} to completely replace coal and oil. Similarly (assuming an efficiency of 40% for an ammonia plant), 2839 Mt of ammonia would be needed to replace NG and 5167 Mt_{NH3} to replace coal and oil.

Furthermore, for hydrogen exists the possibility of carrying out advanced thermodynamic cycles which reckon on direct steam generation, by means of oxy-combustion of hydrogen in special burners/mixture superheaters, which mix the steam already present with that generated by hydrogen combustion. The steam thus obtained is made to expand in a steam turbine, but the thermodynamic efficiency of the cycle is higher with respect to a traditional Hirn cycle because it is possible to exceed the temperature limits, normally dictated by the boiler (Spazzafumo, 2003). To make the most of these cycles would require turbines and materials capable of withstanding high temperatures, which could be developed in years to come.

Synthetic fuels obtained through power to fuel, in particular hydrogen, synthetic methane, methanol, DME and ammonia, can also be used in internal combustion engines for stationary generation, such as those for cogeneration plants. An interesting application of them is also in off grid systems and portable generators which will be treated in the next paragraph. Fuel cells stacks can also be used to obtain a decarbonised and flexible electric energy system at the same time. These have several advantages, in fact they have a high efficiency (today around 50%−55%) and show little or no emissions, moreover they are modular and without moving mechanical parts, which makes construction and management very simple both for a centralised generation plant or a distributed generation system. To date, however, stationary fuel cells still have to face some weaknesses, such as high costs, a shorter lifespan and lower power than turbines. At the moment, therefore, fuel cells seem more suitable for distributed generation, but in the future a normal building could house several modular fuel cell stacks for a zero-emission power plant.

Furthermore, fuel cells, depending on the type of cell, can be fuelled not only with hydrogen, but also with methane, methanol, ammonia, urea and formic acid. If the current generation of electricity from fossil sources in thermoelectric power plants were replaced with synthetic fuels in fuel cells (considering an efficiency of 50%), it would alternatively take 996 Mt_{H2} to totally replace fossil fuels, or 2388 Mt_{CH4}, 6618 Mt of methanol, 6405 Mt_{NH3}, 13,127 Mt of urea or 40,493 Mt of formic acid.

10.4.2 Back-up and off-grid power

Some applications require an uninterrupted supply of electricity even in the event of a blackout, In this case the constant supply of electricity can be guaranteed through uninterruptible power supplies that are activated only when needed.

Moreover there are isolated or mobile applications. In this case power generators are required. Nowadays, most generators for back-up electricity supply or for off-grid applications are internal combustion engines, often fuelled by diesel. Also hybrid systems with diesel generator and batteries or photovoltaic panels and batteries are used, while fuel cells, still not very widespread today, could represent in the near future the optimal solution to reduce emissions in this sector.

The most promising fuel cells for this type of applications currently are those fuelled by hydrogen, methanol or ammonia, directly or after reforming. These systems are used for example for data centres, telecommunication towers, hospitals or rural villages and small islands. Many telecom towers, especially in developing countries, are powered by diesel generators, as they are located in hardly accessible places where the electricity network is absent. Some telecom base stations in South Africa and Kenya are already powered by fuel cells today in the context of experimental projects (Ballard and GSMA, 2013; GenCell, 2018; GSMA, 2019).

Hospitals and clinics, as well as data centres and some banks need protection from blackouts. In this case, dedicated generators or uninterruptible power supplies with fuel cells could be used. In South Africa, a clinic that needs a continuous supply of electricity to refrigerate vaccines and medicines has relied on an uninterruptible power supply with stationary fuel cells since 2015 (Fuel Cells Bulletin, 2006, 2015).

Even in case of emergencies where it is not possible to rely on the electricity grid, such as field hospitals, relief in the event of hurricanes or earthquakes, mobile generators with fuel cells could be used, but also in outdoor events or concerts.

Another case of stationary generation demand may come from nonelectrified rural villages. Some trial project in South Africa have provided electricity to small rural villages using methanol fuel cells with appropriate methanol tanks and batteries (Fuel Cells Bulletin, 2013; ESI Africa's Power Journal, 2014).

10.4.3 Long term and large scale energy storage

Energy storage on a seasonal scale can make possible to balance seasonal variations both in terms of electricity demand and supply. Especially in an energy system strongly or totally based on RES, it will be necessary to store huge amounts of energy. Trying to explore some alternatives, to date, batteries are not yet a fully mature technology, they are very expensive for large plants, suffer from self-discharge over time and, moreover, a huge number of batteries and occupation of large spaces would be required for large-scale storage. This technology nowadays would also require a significant exploitation of rare earths and critical materials for batteries production, such as lithium and cobalt (Yao *et al*., 2016). In a market with high shares of renewables, hydroelectric storage basins (or pumped-hydro), on the contrary now fully mature, will no longer be enough to absorb the grid energy fluctuations, while the construction of new artificial basins, however linked to strictly geomorphological problems, would involve evident impacts in natural environments. Although there are various other alternatives for energy storage, such as flow or solid-state batteries, flywheels and accumulation of compressed air, the best viable solution is the power to fuel technology which does not suffer from losses of stored energy along the time.

One of the advantages of the power to methane technology is the possibility of energy exchange between the electricity grid and the NG network which can be seen as a huge storage basin for renewable sources. As is already the case with the NG infrastructure, synthetic gases can also be stored for entire seasons in underground caves or salt caverns. Salt caverns, thanks to their characteristics of good tightness and low gas contamination, appear very promising in particular for the storage of hydrogen. In addition, other underground storage systems are currently being studied, such as depleted oil or NG fields and pore storage. Ammonia is another suitable synthetic fuel for long-term and large-scale energy storage, since large steel refrigerated tanks are already commonly used in the fertiliser industry for storing liquid ammonia.

Nomenclature

CHP Cogenerated Heat and Power
CNG Compressed Natural Gas
DME DiMethyl Ether
DRI-EAF Direct Reduction of Iron-Electric Arc Furnace

FCEV	Fuel Cell Electric Vehicle
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
NG	Natural Gas
PEMFC	Proton Exchange Membrane Fuel Cell
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuels
SCR	Selective Catalytic Reduction
TFC	Total Final Consumption
TPES	Total Primary Energy Supply

References

Altfeld, K., and Pinchbeck, D. (2013). Admissible hydrogen concentrations in natural gas systems. *Gas for Energy*, *March/2013*, 1−16. Available at: https://www.gas-for-energy.com.

ANT Energy Solutions (2013) 'Renewable Hydrogen Market Report'.

Asian Rehub (2020) *Asian Renewable Energy Hub Project*. Available at: https://asianrehub.com/ (Accessed: 22 December 2020).

Balestri, M. *et al*. (2007) 'Enel's Fusina hydrogen-fed power generation plant', *2007 International Conference on Clean Electrical Power, ICCEP '07*, pp. 456−463. https://doi.org/10.1109/ICCEP.2007.384254.

Ballard and GSMA (2013) *Fuel Cell Systems for Telecom Backup Power*. Available at: https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2013/06/Ballard-Power-Systems.pdf.

CNN (2020) *Bill Gates, Amazon and British Airways are backing a hydrogen plane startup*. Available at: https://edition.cnn.com/2020/12/16/business/zeroavia-hydrogen-planes/index.html (Accessed: 22 December 2020).

Dimitriou, P., and Javaid, R. (2020). A review of ammonia as a compression ignition engine fuel. *International Journal of Hydrogen Energy*, *45*(11), 7098−7118. Available from https://doi.org/10.1016/j.ijhydene.2019.12.209, Elsevier Ltd.

Ditaranto, M., Heggset, T., and Berstad, D. (2020). Concept of hydrogen fired gas turbine cycle with exhaust gas recirculation: assessment of process performance. *Energy*, *192*, 116646. Available from https://doi.org/10.1016/j.energy.2019.116646, Elsevier Ltd.

EIA (2019) *International Energy Outlook 2019 - with projections to 2050*. Washington, DC 20585: U.S. Energy Information Administration. Available at: https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf.

ENE-FARM (2020) *Panasonic Launches New 'ENE-FARM' Product, a Fuel Cell for Condominiums - FuelCellsWorks*. Available at: https://fuelcellsworks.com/news/panasonic-launches-new-ene-farm-product-a-fuel-cell-for-condominiums/ (Accessed: 30 November 2020).

ENEL (2009) ENEL: first hydrogen-fuelled power now on-line in Venice. Available at: https://corporate.enel.it/en/media/press/d/2009/08/enel-first-hydrogen-fuelled-power-now-on-line-in-venice- (Accessed: 21 December 2020).

ESI Africa's Power Journal (2014) *Methanol Fuel Cells trialled to power rural South African towns*. Available at: https://www.esi-africa.com/top-stories/methanol-fuel-cells-trialled-to-power-rural-south-african-towns/ (Accessed: 23 December 2020).

European Commission (2002) *Liquid hydrogen fuelled aircraft - system analysis (CRYOPLANE project)*. Available at: https://cordis.europa.eu/project/id/G4RD-CT-2000-00192/it (Accessed: 22 December 2020).

EUTurbines (2019) *The gas turbine industry commitments to drive Europe's transition to a decarbonised energy mix (press release)*. Available at: https://powertheeu.eu/wp-content/themes/euturbines/dl/EUTurbines-press-release-on-the-Commitments.pdf.

Fuel Cells Bulletin. (2006). Intelligent energy fuel cells showcased in S. Africa. *Fuel Cells Bulletin*, *2006*(4), 1. Available from https://doi.org/10.1016/S1464-2859(06)70995-6.

Fuel Cells Bulletin. (2013). SA supports Ballard, Anglo American fuel cells deployment. *Fuel Cells Bulletin*, *2013*(7), 6. Available from https://doi.org/10.1016/s1464-2859(13)70255-4.

Fuel Cells Bulletin. (2015). South African clinic using fuel cell power to benefit TB patients. *Fuel Cells Bulletin*, *2015*(10), 5. Available from https://doi.org/10.1016/s1464-2859(15)30308-4.

FuelCellsWorks (2019) *South Korea: Work Begins on World's Largest Hydrogen Fuel Cell Power Plant*. Available at: https://fuelcellsworks.com/news/south-korea-work-begins-on-worlds-largest-hydrogen-fuel-cell-power-plant-commissioned/ (Accessed: 23 December 2020).

GenCell (2018) *Adrian Kenya Selects New GenCell A5 Fuel Cell Solution to Provide Green, Off-Grid Power to 800 Telecom Base Stations*. Available at: https://www.gencellenergy.com/news/adrian-kenya-800-telecom-base-stations/ (Accessed: 23 December 2020).

Global Railway Review (2020) *Alstom awarded Germany contract for supply of 30 Coradia Lint trains*. Available at: https://www.globalrailwayreview.com/news/98798/alstom-germany-contract-coradia-lint-trains/ (Accessed: 22 December 2020).

Goldmeer, J. (2018) 'Fuel flexible gas turbines as enablers for a low or reduced carbon energy ecosystem', (May).

Grand View Research (2019) *Methanol Market Size, Share & Trends Analysis Report By Application (Formaldehyde, Acetic Acid, MTBE, DME, Fuel Blending, MTO, Biodiesel), By Region, And Segment Forecasts, 2019 - 2025*. Available at: https://www.grandviewresearch.com/industry-analysis/methanol-market (Accessed: 24 December 2020).

GSMA (2019) *Case Study: GenCell*. Available at: https://www.gsma.com/futurenetworks/wiki/case-study-gencell/ (Accessed: 23 December 2020).

H21 (2018) *H21 North of England*. Available at: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf.

Herdin, G. *et al*. (2007) 'Hydrogen and hydrogen mixtures as fuel in stationary gas engines', *SAE Technical Papers*, (724). doi: 10.4271/2007-01-0012.

Hsieh, J. (1979) *U.S. Patent 4160663A - Method for the direct reduction of iron ore*.

HYBRIT Project (2019) *HYBRIT - Towards fossil-free steel*. Available at: http://www.hybritdevelopment.com/ (Accessed: 21 September 2020).

ICAO. (2018). *Sustainable Aviation Fuels Guide*. International Civil Aviation Organisation.

IEA. (2019a). Key World Energy Statistics, International Energy Agency. Paris: IEA Available at. Available from https://www.iea.org/reports/key-world-energy-statistics-2020.

IEA. (2019b). The Future of Hydrogen—Seizing today's opportunities—Report prepared for the G20, Japan, International Energy Agency. Paris: IEA Available at. Available from https://webstore.iea.org/download/direct/2803.

IEA. (2019c). World Energy Balances, International Energy Agency. Paris: IEA Available at. Available from https://www.iea.org/reports/world-energy-balances-overview.

International Maritime Organization (2018) *Adoption of Initial IMO Strategy on Reduction of GHG Emissions from Ships, Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue*.

IVECO (2020) *Natural Gas Powered Vehicles*. Available at: https://www.iveco.com/en-us/press-room/kit/Pages/E3-NaturalGasPoweredVehicles.aspx (Accessed: 22 December 2020).

Kippers, M.J. *et al*. (2011) *Pilot project on hydrogen injection in natural gas on island of Ameland in The Netherlands, International Gas Union Research Conference Proceedings*. Apeldoorn, Netherlands. Available at: http://members.igu.org/old/IGUEvents/igrc/igrc2011/igrc-2011-proceedings-and-presentations/posterpaper-session1/P1-34_MathijsKippers.pdf.

Krüger, A., et al. (2020). Integration of water electrolysis for fossil-free steel production. *International Journal of Hydrogen Energy*, *45*(55), 29966−29977. Available from https://doi.org/10.1016/j.ijhydene.2020.08.116.

Leo, A. and FuelCell Energy (2016) 'Stationary Fuel Cell Power Systems with Direct FuelCell Technology Tackle Growing Distributed Baseload Power Challenge'. Available at: http://www.fuelcellenergy.com/wp-content/uploads/2016/10/Fuel-Cell-Technology-White-Paper.pdf.

MAN Energy Solutions (2019) 'Engineering the future two-stroke green-ammonia engine'. Available at: https://marine.man-es.com/docs/librariesprovider6/test/engineering-the-future-two-stroke-green-ammonia-engine.pdf?sfvrsn = 7f4dca2_4.

Market Research Future (2020) *Ammonia Market by Size, Share, Type and Research Analysis − 2028*. Available at: https://www.marketresearchfuture.com/reports/ammonia-market-2405 (Accessed: 21 December 2020).

McKinsey and Company, Clean Sky 2 JU and Fuel Cell and Hydrogen 2 JU (2020) *Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050, Publications Office of the European Union*. Belgium. https://doi.org/10.2843/766989.

Mitsubishi Power (2019) *Hydrogen Power Generation Handbook*. Available at: https://power.mhi.com/catalogue/pdf/hydrogen_en.pdf.

Moliere, M. (1999) 'Heavy duty gas turbines in petrochemical plants: Samsung's Daesan plant (Korea) beats fuel flexibility records with over 95% hydrogen in process gas', *Proceedings of the PowerGen Asia Conference*, (September).

Muraki, S. (2018) 'Energy Carriers - Becoming a New Energy Society', *Cross-ministerial Strategic Innovation Promotion Program (SIP)*.

Nagashima, M. (2018) *Japan's hydrogen strategy and its economic and geopolitical implications, Études de l'Ifri*. Ifri.

Nielsen, E.R. and Prag, C.B. (2017) *Learning points from demonstration of 1000 fuel cell based micro-CHP units - Summary of analysis from the ene.field project*. Available at: http://enefield.eu/wp-content/uploads/2017/10/ene.field-Summary-Report.pdf.

Power Magazine (2020) *JERA Planning to Shift Coal Power Fleet to 100% Ammonia*. Available at: https://www.powermag.com/jera-planning-to-shift-coal-power-fleet-to-100-ammonia/ (Accessed: 23 December 2020).

Shiozawa, B. (2019) '"SIP Energy Carriers" Updates and Establishment of Green Ammonia Consortium'.

Snam (2020) *Agreement between Alstom and Snam for the development of hydrogen trains in Italy*. Available at: https://www.snam.it/en/Media/Press-releases/Agreement_Alstom_and_Snam_hydrogen_trains_in_Italy.html (Accessed: 22 December 2020).

Spazzafumo, G. (2003). An Overview of Thermodynamic Cycles Based on Direct Stoichiometric Combustion of Hydrogen and Oxygen. *Journal of Scientific & Industrial Research*, *62*(January−February), 71−80.

Tian, P., et al. (2015). Methanol to olefins (MTO): From fundamentals to commercialization. *ACS Catalysis*, *5*(3), 1922−1938. Available from https://doi.org/10.1021/acscatal.5b00007.

Toshiba (2017) *Toshiba's 100kW Pure Hydrogen Fuel Cell System Realizing CO2 Free Electricity Generation is now Operating in Japan*. Available at: https://www.toshiba.co.jp/about/press/2017_04/pr2701.htm (Accessed: 23 December 2020).

Towoju, O. A., and Dare, A. (2017). Di-methyl ether (DME) as a substitute for diesel fuel in compression ignition engines. *International Journal Of Advanced Research in Engineering & Management (IJAREM)*, 39−47, March.

Valera-Medina, A., et al. (2018). Ammonia for power. *Progress in Energy and Combustion Science*, *69*, 63−102. Available from https://doi.org/10.1016/j.pecs.2018.07.001, Elsevier Ltd.

van Wijk, A. and Noordelijke Innovation Board (2017) *The Green Hydrogen Economy now in the Northern Netherlands*. Groningen, the Netherlands.

Vavra, J., Bortel, I., and Takats, M. (2019). *A dual fuel hydrogen—diesel compression ignition engine and its potential application in road transport*. *SAE Technical Paper*. SAE International. https://doi.org/10.4271/2019-01-0564.

Verhelst, S., and Wallner, T. (2009). Hydrogen-fueled internal combustion engines. *Progress in Energy and Combustion Science*, *35*(6), 490−527. Available from https://doi.org/10.1016/j.pecs.2009.08.001.

Wang, T., et al. (2014). *Conversion of methanol to aromatics in fluidized bed reactor*. *Catalysis Today* (233, pp. 8−13). Elsevier B.V. https://doi.org/10.1016/j.cattod.2014.02.007.

Yao, L., et al. (2016). Challenges and progresses of energy storage technology and its application in power systems. *Journal of Modern Power Systems and Clean Energy. Springer Berlin Heidelberg*, *4*(4), 519−528. Available from https://doi.org/10.1007/s40565-016-0248-x.

Ye, L., et al. (2017). Reaction: "green" ammonia production. *Chem*, *3*(5), 712−714.