Hydrogen Role on the Decarbonization Transition Route

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1. Introduction

Awareness of climate change impacts and the need for deep decarbonization has increased greatly in recent years. In 2018 the EU published its vision for the future of energy in Europe 'A Clean Planet for All' which aims at creating a "prosperous, modern, competitive and climate neutral economy by 2050." A set of pathways has been developed and assessed that rely heavily on renewable energy and energy efficiency, with a role for natural gas and hydrogen.

The need to accelerate clean energy transitions is underscored by recent data: CO_2 emissions rose for a second year in a row in 2018 to reach a record high.

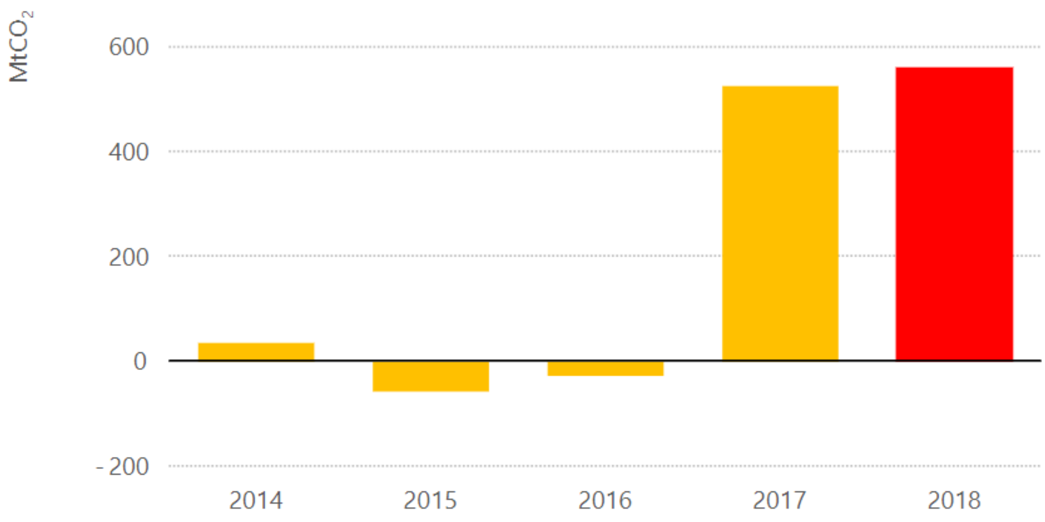

Figure 1 Annual change in global energy-related CO_2 emissions, 2014-2018[1]

In response to this growing awareness and the urgency of decarbonization, policy makers have taken action and in 2015 agreed to what is known as the Paris agreement. This has set the target to limit the expected global average temperature increase to significantly less than 2°C, with the ambition to keep to the limit to less than 1.5°C. In order to achieve such necessary and ambitious targets, the European economy, and in particular the energy sector, needs to significantly reduce CO_2 emissions to a fraction of current levels (e.g. -80%, -95%) with a growing consensus that net zero emissions will be required. Many changes will be required in how we work, travel, heat our homes and how we obtain the energy necessary to carry out all these activities, as shown in Figure 2.

[1] IEA 2019

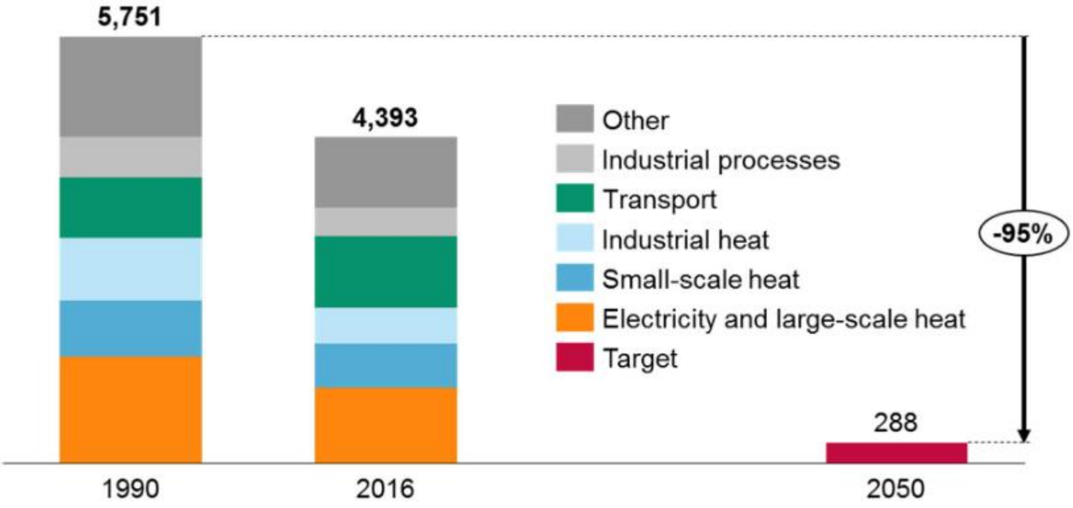

Figure 2 The scale of Europe's decarbonisation challenge – emissions by sector (MtCO2e)[2]

Hydrogen can help overcome many difficult energy challenges:

- Integrate more renewables, including by enhancing storage options & tapping their full potential
- Decarbonize hard-to-abate sectors – steel, chemicals, trucks, ships & planes
- Enhance energy security by diversifying the fuel mix & providing flexibility to balance grids

Either if there are challenges:

- costs need to fall;
- infrastructure needs to be developed;
- cleaner hydrogen is needed;
- regulatory barriers persist.[3]

A key feature of hydrogen is its ability to act as both a source of clean energy (for a variety of uses), and an energy carrier for storage. Hydrogen can be transported through existing pipelines, mixed with natural gas, and through dedicated pipelines in the future. It offers an energy storage solution that costs ten times less than batteries.

Hydrogen is already widely used for industrial purposes across the steel, petrochemical and food sectors, but it is now also being used in mobility. In the future, it could also replace natural gas to heat residential and commercial buildings. Hydrogen can also be transformed into clean electricity by injecting it into fuel cells.

[2] Source: 2016 National Inventory Submissions (Common Reporting Format) for EU, Norway and Switzerland Note: Transport here refers to ground-based transport. Aviation and waterborne transport are counted towards the 'Other' segment

[3] IEA, 2019

The most interesting thing about hydrogen, is that it does not generate carbon dioxide emissions or other climate-changing gases, nor does it produce emissions that are harmful for humans and the environment. For this reason, it will play a key role in ensuring that European and global decarbonisation objectives are achieved by 2050.[4]

Low-carbon hydrogen from fossil fuels is produced at commercial scale today, with more plants planned. It is an opportunity to reduce emissions from refining and industry.

Figure 3 Hydrogen production with CO_2 capture is coming online[5]

2. Hydrogen Economy

The *hydrogen economy* is an energy system based on hydrogen for energy storage, distribution and utilisation (Figure 4). The concept was conceived because of concerns over the stability of petroleum and gas reserves and the potential lack of stable energy sources. This situation made governments and industries in several countries consider alternative strategies to implement an energy system based on hydrogen as a clean, potentially renewable, fuel. Hydrogen was thus considered an ideal candidate as a carrier of energy, in much the same way as electricity. To be sustainable it must be produced from a natural resource using renewable energy or materials.

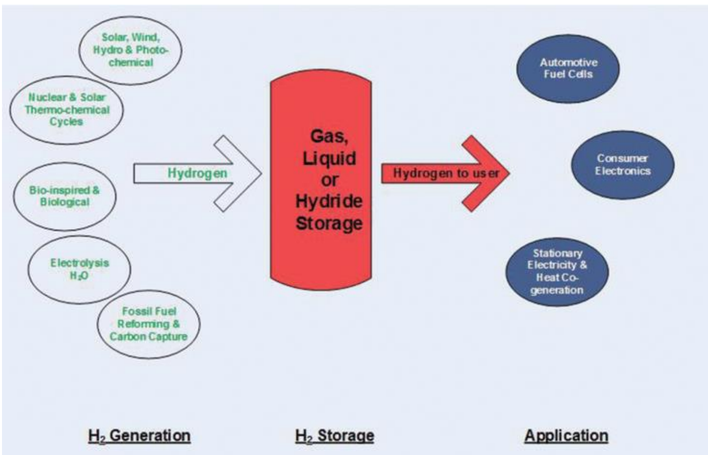

Figure 4 The hydrogen economy or hydrogen energy system. A network of primary energy sources geared to hydrogen generation and storage to support multiple power applications[5].

[4] https://www.snam.it/en/hydrogen_challenge/hydrogen_energy_transition/

[5] Keith Scott, Chapter 1: Introduction to Electrolysis, Electrolysers and Hydrogen Production, in Electrochemical Methods for Hydrogen Production, 2019, pp. 1-27 DOI: 10.1039/9781788016049-00001 eISBN: 978-1-78801-604-9

Hydrogen is a suitable basis for an energy system because it has a number of attractions:

- It is the most abundant element in the world, although almost exclusively in combination with other elements, notably oxygen as water
- It can be obtained readily from water
- It has very good chemical activity
- When combusted or reacted with oxygen it has zero emissions characteristics – the product is water
- It has the highest gravimetric energy density of any known fuel
- It is compatible with both electrochemical and combustion processes
- It has very good electrochemical activity
- It is very compatible with fuel cell applications

There are of course several challenges to the implementation of hydrogen into an energy system and these include both societal and technical barriers such as:

- Hydrogen occurs almost exclusively in combination with other elements and is not immediately accessible as fuel without significant energy input.
- Hydrogen buoyancy and flammability must be accounted for in its safe use and storage.
- Hydrogen production is currently mainly from non-renewable fossil fuels.
- Hydrogen's energy storage and distribution infrastructure is limited worldwide.
- Hydrogen containment at technical levels on a volume basis is lower than liquid fuels.
- Hydrogen has unique permeability characteristics through many materials and can result in material embrittlement.
- Hydrogen has large investment costs in its manufacture and production for worldwide, large-scale use.

2.1 Hydrogen Production

Steam methane reforming (SMR) and auto-thermal reforming (ATR) are thermal processes already used today. The process reacts methane (CH_4) with steam to produce hydrogen and CO_2. In order to be carbon-neutral, it needs to be combined with carbon capture and storage (CCS) of the CO_2 produced. The key advantage of this technology is that it is currently the most developed option, especially at scale, and as such presents the most cost-effective form of hydrogen production even with the addition of CCS. Drawback is the need for complex storage of CO_2, which is not available in all countries and faces political opposition in many countries.

Electrolysis is another existing technology that splits water (H_2O) into hydrogen and oxygen using electricity. The hydrogen produced can be only be considered zero carbon if the electricity used is itself zero carbon. The fact that there are no direct carbon emissions and no other by-products that need to be stored, make this option attractive, although there are questions around higher cost and scalability.

Pyrolysis is the decomposition of methane into hydrogen and solid carbon (C). A developing technology[6] that has the potential to play an important role in hydrogen production in the future. This is because the carbon is in solid rather than in gaseous form and therefore requires no complex storage in underground

[6] IEA. "The future of hydrogen 544report." 2019

caverns, as is the case with CCS. Solid carbon can be used in existing industries, such as carbon black for tyres, inconcrete for construction, or new uses such as graphene.

Other ways of producing hydrogen such as coal gasification, oil partial oxidation, algae photosynthesis, wood pyrolysis, or based on ethanol and methanol can be used but they are not economic competitive.

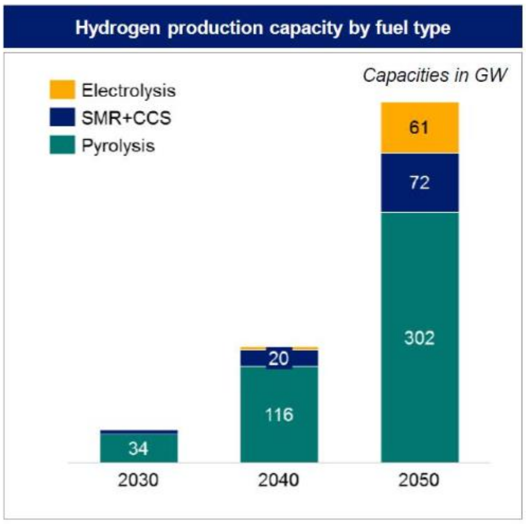

Figure 5 Green Hydrogen Production Forecast[7]

Currently 76% of world hydrogen production is from natural gas, using steam methane reforming, partial oxidation or auto-thermal reforming, and 23% from coal gasification. Hydrogen production by any of these methods requires CCS to avoid CO_2 emissions.

<u>Remark</u>

It should be noted that:

- ✓ electrolysis, while not leading to any direct emissions, can only be regarded as truly carbon neutral if the electricity that is used as an input into the process has been produced from a zero carbon source. If electricity is produced from a fossil fuel source without CCS, such as coal or natural gas, hydrogen from electrolysis would be associated with indirect carbon emissions.
- ✓ SMR with CCS will be difficult in some countries, due to political and technical reasons.[8]
- ✓ Different processes can be used in pyrolysis including thermal, catalytic and plasma-based technologies. The energy required for the pyrolysis reaction can be provided by electricity (for example from renewables) or from the natural gas feedstock or the hydrogen produced as part of the process. If biogas or biomethane are used as a feedstock then the process can result in negative emissions.[9]

[7] Poyry, 2019; Global ESG Conference, Rome, 11 October 2019
[8] Hydrogen from natural gas –The key to deep decarbonisation; Discussion Paper commissioned by Zukunft ERDGAS – July 2019.
[9] IEA. "The future of hydrogen." 2019

3. Storage of Hydrogen

Hydrogen must be conveniently stored and readily available for dispensing for a range of applications, including transportation, portable devices and large-scale stationary power generation. The storage of hydrogen is one of the fundamental requirements for the evolution of the hydrogen energy system.

There are currently three principle methods available for hydrogen storage:

- as a pressurized gas,
- as a cryogenic liquid
- as a metal hydride

A major challenge for effective hydrogen storage is related to its physical properties. It is a light gas with a molar mass of 2, and thus has a high energy density availability based on the mass principle and it has one of the lowest energy storage densities based on unit volume. Hydrogen storage requires the reduction of an enormous volume of gas and an objective in hydrogen storage is to pack hydrogen as close as possible, i.e. to reach the highest volumetric density, using as little additional material and energy as possible. To increase the density of hydrogen, either work must be applied to compress the gas, or the temperature must be decreased below the critical temperature to liquefy it. Alternatively, the molecular repulsion can be reduced by the interaction (chemically or physically) of hydrogen with another material. Storage of hydrogen as a gas uses very high pressures. Cryogenic storage of hydrogen as a liquid is not straightforward, requiring a reduction in temperature to 22 K, and even then, the density is still modest at 71 $kg\,m^{-3}$.

Hydrogen occurs in many forms. It can occur as an anion (H^-) or cation (H^+) in ionic compounds, form covalent bonds e.g. with carbon, and behave like a metal to form alloys or inter-metallic compounds at ambient temperature. The chemical storage of hydrogen with other elements can be achieved with reasonable volumetric energy densities, but an important issue for a hydrogen storage system is the reversibility of the chemical combination and the release of hydrogen from the "host" material. The reversibility criterion excludes all covalent hydrogen-carbon compounds, as with these, hydrogen is only released when they are heated to temperatures above 800 °C or if the carbon is oxidized. The methods for reversible hydrogen storage which provide a high volumetric and gravimetric density known today are:

- conventional storage methods, i.e. high-pressure gas cylinders or as liquid hydrogen;
- the physi-sorption of hydrogen on materials with a high specific surface area [many forms of carbon (nanotubes, nanofibres, fullerenes, activated charcoals, other forms of nanoporous carbon, etc.); other inorganic nanoporous materials];
- hydrogen intercalation in metals and complex hydrides;
- storage of hydrogen based on metals and water;
- as inorganic and organic liquids and solids.

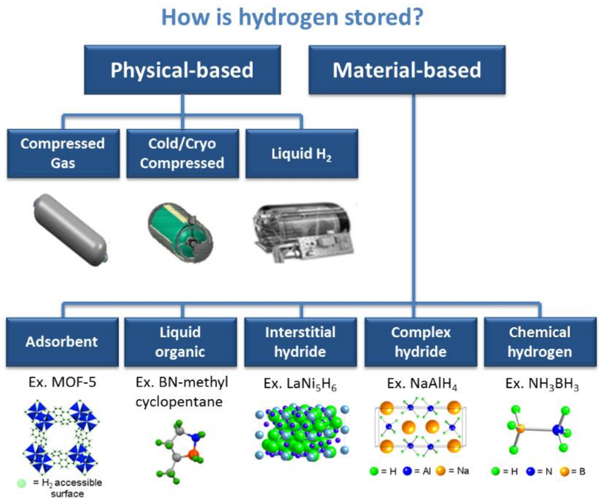

Figure 6 Hydrogen Storage Methods

For storage in stationary systems, steel tanks are a suitable method, as weight and size are not important. For transportation, the traditional tanks do not represent an adequate solution due to their additional weight, which can be more than the weight of the stored hydrogen, and volume needed to store the gas. Over recent years there have been significant developments in new types of composite storage tanks that can store hydrogen at 300–800 bar pressure, at which hydrogen can reach a gas density of 36 kg m^{-3}, which is approximately half that of its liquid form at its normal boiling point. These types of storage tank have a capacity of 10–18 wt% of hydrogen. Further developments are taking place to use lightweight composites that will meet the requirements for an acceptable driving range for automobiles, as well as safety requirements related to potential collision damage. Of course, the issue of compression of hydrogen to these pressures is an important consideration due to the associated energy costs and the need for specialized compressors. Storage of hydrogen above pressures of 1000 bar would on first sight seem to be a way of increasing capacity. But hydrogen is a non-ideal gas and its compressibility factor increases with pressure applied such that at such high pressures it approaches a maximum in volumetric storage capability.

As an energy store, hydrogen has high energy storage capabilities (

Figure 7) with a gravimetric storage capability of 38 kWh kg^{-1} as a liquid. Unfortunately, hydrogen has a relatively low volumetric energy storage capability which is one of the major challenges in its use, when space is at a premium. Hence for transportation applications and other applications where volume is at a premium the storage of hydrogen is a greater challenge. Sufficient fuel must be stored to make it practical to drive distances comparable to petrol- or diesel-powered cars. For example, the energy content of 1.0 kg hydrogen is approximately equal to 3 kg petrol (∼4 litres). Thus, an average tank of some 60 litres requires an equivalent storage for 15 kg H_2. An 800 bar storage tank (hydrogen gas density = 40 kg m^{-3}) would thus need to have a volume for hydrogen of 375 litres, i.e. some six times that of a petrol tank.

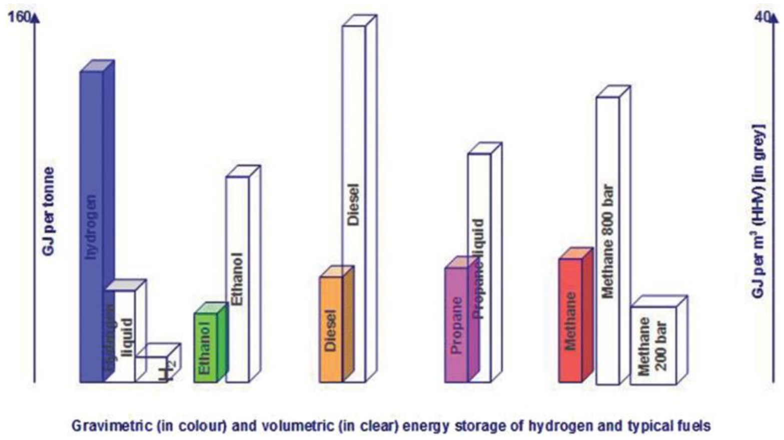

Figure 7 Comparison of energy storage of hydrogen with other fuels.[10]

However, the challenge faced for hydrogen storage is trying to compete with the energy density of petrol, which is much greater than hydrogen, in either liquid, hydride or gaseous form. For hydrogen, that added weight of the container is an additional and major factor which significantly affects its ability to compete with petrol. As a means of comparison to illustrate the challenge faced in hydrogen storage, Table 1 shows the volume density of hydrogen stored in several compounds and liquid hydrocarbons.[11] The volumetric energy densities of those compounds (except graphite monolayers) are higher than that of hydrogen as liquid or as compressed gas (at approximately 700 bar). The most effective hydrogen storage media (ignoring the organic chemical compounds) which provide the highest mass fraction and volume density for hydrogen are based on light elements such as lithium, nitrogen, boron and carbon. Ammonia is considered a potential storage compound for hydrogen because of its known chemistry of formation from nitrogen and hydrogen, which is the basis for its formation for the synthesis of fertilisers. Hydrocarbon-based compounds, e.g. methanol and octane, are both liquid and high-density hydrogen storage compounds and high energy density fuels.

Method	Storage capacity, wt% of hydrogen	Volumetric capacity, Mass kg_{H_2} per litre
Metal hydrides $FeTiH_2$ and $LaNi_5H_6$, Mg_2NiH_4	~2	0.115–0.145
Pressurised H_2 gas (330 bar)	5	0.05
Cryogenic liquid H_2 (20K)	100	0.066
Solid H_2	100	0.08
Methanol	12.5	0.1
Methane (liquid)	25	0.105
Gasoline (C16)	15	0.12
Ammonia	17	0.103
$LiBH_4$	18	0.125
$NaBH_4$	11	0.115

Table 1 Comparison of energy density storage characteristics for hydrogen.

[10] Keith Scott, Chapter 1:Introduction to Electrolysis, Electrolysers and Hydrogen Production , in Electrochemical Methods for Hydrogen Production, 2019, pp. 1-27; DOI: 10.1039/9781788016049-00001

[11] X. Wu and K. Scott , J. Mater. Chem., 2011, 21 , 12344

An alternative to the storage of hydrogen in chemical compounds is to store it by adsorption onto a solid surface.

The compound with the highest gravimetric hydrogen density today is $LiBH_4$ (18 mass%). This complex hydride could, therefore, be the ideal hydrogen storage material for mobile applications. $LiBH_4$ desorbs three of its four hydrogens upon melting at 280 °C and decomposes into LiH and boron.

$$LiBH_4 \leftrightarrow LiH + B + 1.5\ H_2$$

The desorption of hydrogen on these compounds can be catalysed by adding SiO_2 and significant thermal desorption has been observed, starting at 100 °C.

4. Cost of Hydrogen Production

Dedicated hydrogen production is concentrated in very few sectors today, and virtually all of it is produced using fossil fuels, as a result of favourable economics.

Hydrogen production costs are expected to fall over time, as the technologies develop.

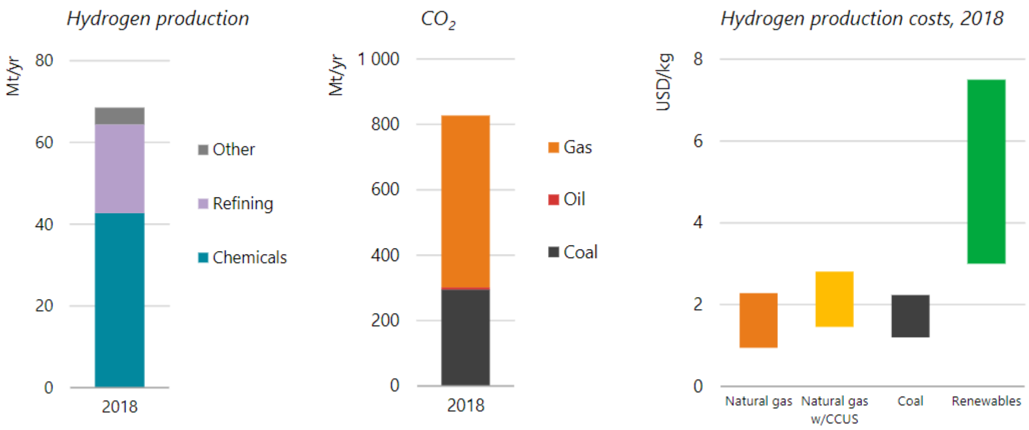

Figure 8 Hydrogen Production and Costs[5]

The key parameters for the hydrogen production technologies are given in the table below. Notably missing from this table are costs for feedstocks, since those change over the course of years, days (and, in the case of electricity, hourly).[12]

	Capex (€/kW H2)	Opex (€/kW H2/yr)	Efficiency	Levelised cost[1]
SMR with CCS	934	37	78	47
Pyrolysis	1261	22	55	60
Electrolysis	544	31	80	66

[1] Assumes baseload operation of SMR and pyrolysis and a gas price of €20/MWh. For electrolysis, this assumes a 30% load factor and average electricity price of €30/MWh (assuming that the electricity price for the lowest priced periods for 30% of the time is €30/MWh on average). In order to achieve a higher load factor, electrolysers would have to buy electricity during periods when it was more expensive, thereby increasing the input price of electricity, and leading to higher levelized costs for the hydrogen produced. It does not make economic sense to overbuild renewable generation to enable cheap electricity for electrolysis [13].

[12] Pyrolysis: Pöyry analysis based on Brett Parkinson, P. Balcome et al. "Hydrogen production using methane: Techno-economics of decarbonizing fuels andchemicals." 2017

[13] Hydrogen from natural gas –The key to deep decarbonisation; Discussion Paper commissioned by Zukunft ERDGAS – July 2019.

The key drivers for the wholesale costs of hydrogen are:

- technology costs: capex occupies a large share within the total cost of all hydrogen production technologies, especially for electrolysis;
- input price: the cost of gas and electricity are important drivers for the cost of hydrogen – higher gas prices and/or lower electricity prices (i.e. cheaper than expected renewables) could make electrolysis more economical relative to SMR with CCS or pyrolysis;
- cost of CO_2 storage: SMR with CCS depends on the cost of transportation and storage of CO_2;
- value of solid carbon products: markets for solid carbon products already exist but are relatively limited. If additional demand for solid carbon products materialises, pyrolysis can benefit from an additional revenue stream, thereby making it more commercially attractive.

4.1 Cost advantages of hydrogen production from natural gas

The main drivers of hydrogen production costs are the fixed costs and the 'input price' – either electricity or natural gas. The competitiveness of electrolysis versus either SMR with CCS or pyrolysis is therefore dependent on the relative prices for electricity and natural gas.

Renewables are inherently intermittent and only generate electricity when wind speeds or solar irradiation are sufficient. Neither is it 'dispatchable' unlike coal and gas generation, meaning that the electricity system operator cannot call upon renewable generation to produce electricity when it is required by the system. The lack of control over renewable generation means that, at times, there may be too little available to meet demand and therefore 'back-up' dispatchable generation is required. At other times, there may be an excess of renewable generation over demand leading to the 'curtailment' or switching-off of wind and solar, associated

The competitive production of hydrogen by electrolysis depends on a significant number of these periods of low, zero or negatively priced electricity, as it can be more economical to produce hydrogen when electricity prices are low as an alternative to curtailment. The increase in the frequency of very low prices in several European markets in recent years (most notably in Germany) has led to a surge in the interest in electrolysers to produce hydrogen[6].

The practical benefits of zero carbon hydrogen from natural gas become clear when we consider the logistics of hydrogen production and supply. Aside from the issues associated with the scale and costs of electrolysis, it needs to be also considered the locations of hydrogen production. If hydrogen is produced from electrolysis, it will need to be produced in areas and regions with a strong potential for renewable electricity in order to be economic. (Using nuclear power for electrolysis would be much more expensive). Examples are Iberia and Southern Italy for solar PV, and the North Sea region for wind. In such a case, hydrogen would then have to be transported via transmission pipelines over hundreds of kilometres to demand centres that could be in different countries. A hydrogen transmission network would need to be developed – either by repurposing the existing gas transmission network or by constructing new hydrogen transmission pipelines. In that case, there would be also be a requirement for many new transmission connection points linking both renewables generation to the electrolysers, and the electrolysers to the hydrogen transmission grid. This would increase costs and complexity significantly.

The alternative, and more feasible, approach is to produce hydrogen from natural gas closer to demand centres, thus removing the requirement for a hydrogen transmission network to be developed.

Existing gas transmission pipelines could continue to carry natural gas throughout Europe, as they do today. Natural gas would be offtaken from the transmission grid and then converted into hydrogen before being injected into the distribution grid. This would limit any disruption and conversion necessary to the distribution networks.

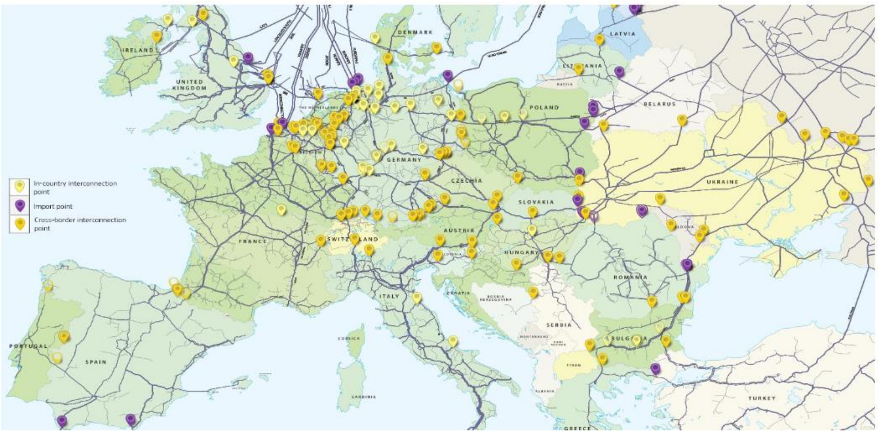

Figure 9 The European Gas Grid – cheap transport of H_2[14]

Continuing to use the transmission networks to transport natural gas, whilst producing hydrogen at the local level, also enables a more feasible transition to a decarbonised economy. Whilst the gas transmission networks continue to carry natural gas, individual distribution networks can be converted to carry hydrogen in a phased and planned roll out. If the transmission grid were converted to hydrogen, all the connecting distribution grids and their customers would have to be ready to switch to hydrogen at the same time.

5. Energy Transition

The reason for the growing momentum behind hydrogen is the insight that existing gas infrastructure can be used to transport hydrogen, with limited adjustments and costs in the gas grid in a transition phase. This significantly enhances the potential of hydrogen. Carbon emission savings would depend on the quantity of zero carbon hydrogen blended, and limits for this in countries vary.

Figure 10 Four key opportunities for scaling up hydrogen to 2030 [15]

[14] https://www.entsog.eu/; 2019
[15] IEA 2019

Natural gas, and the hydrogen produced from it, will continue to utilise existing European gas assets including LNG import terminals, storages and pipeline interconnections. The existing European gas infrastructure has been developed over many years and has a proven track record of providing secure gas and secure supply routes into Europe.

There will also be advantages to electricity security of supply as existing generating assets can be converted to operate on hydrogen rather than natural gas. This will enable dispatchable generation (CCGTs, Combined Cycle Gas Turbines and OCGTs, Open Cycle Gas Turbine) to continue to provide flexibility and back-up to renewable generation. These plants would be used in the same way as today, and will also help avoid investment in more expensive options, such as grid battery storage.

It is clear that there is not one single solution that can solve all challenges with decarbonisation. Therefore, in order to ensure consumers, have a choice but also to ensure the competitiveness of European industry, competition in all parts of the energy sector is vital. Utilising natural gas as the main source of hydrogen production contributes to competition in the energy markets.

6. Hydrogen towards deep decarbonization

The term "hydrogen economy" was coined in 1970 by the University of Pennsylvania electrochemist Bernhardt Patrick John O'Mara Bockris. His vision was to provide clean power without the pollution generated by fossil fuel sources. Researchers have been exploring the hydrogen cycle since then, focusing on the need to efficiently generate, store, and distribute hydrogen for power generation, ammonia production, reduction of metals, and other applications. Materials development and discovery have been at the heart of these efforts.

Though the hydrogen economy concept is not new, the motivation of resurgence changes over time like shown in the figure below.

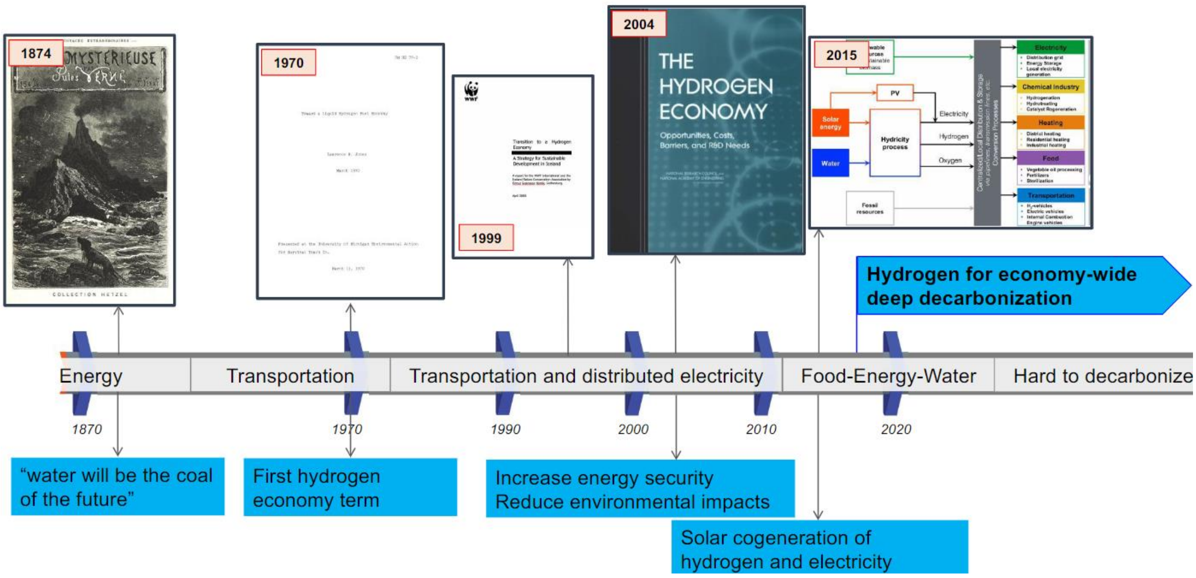

Figure 11 Power to Hydrogen concept development [16]

[16] EIA, 2018

The exact integration of hydrogen into the energy system is uncertain but numerous opportunities exist both on the supply and demand side.

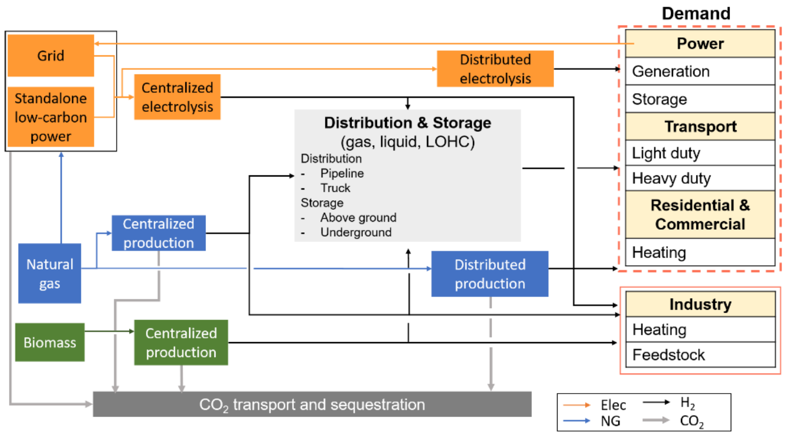

Figure 12 Hydrogen integration into the energy system[17]

Hydrogen value chain should be significantly scaled-up to have an impact in the current energy system –2018 H_2 production ~10 Mtons (1.2 EJ) vs. 2018 energy demand ~101.2 Quad (106.8 EJ)

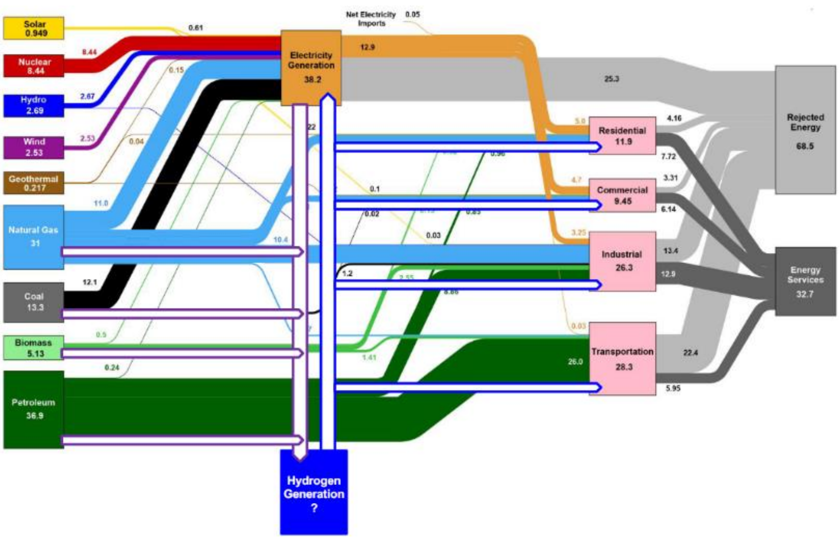

Figure 13 Power Generation Chain [18]

6.1 Different pathways to decarbonization

Renewables will play a significant role in all pathways as a cost-effective form of clean energy in the future.

Hydrogen has an essential role in the heat and transport sectors. Hydrogen provides a feasible and practical option for those sectors and applications that are very difficult, or impossible, to electrify. These include:

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[17] MITEI Spring Symposium–Cambridge, MA; 2019

[18] Lawrence Livermore National Laboratory, 2018

- Industrial process heat. Very high temperature process heat applications (e.g. glass production, plastics and rubber manufacturing) cannot be electrified and otherwise can only decarbonise with biomass or CCS. This, in turn, introduces supply chain, political, and technical issues;
- Space heating. Many buildings are unsuitable for the use of heat pumps (e.g. poor insulation, cold weather, no space for radiators or underfloor-heating, excessive disruption to homes or businesses);
- Heavy road transport. It is impractical to use very large batteries / overhead lines for the haulage sector;
- Waterborne transport. Electrification is not feasible due to long journeys and therefore extended periods between possible re-charging.

In order for hydrogen to play a role in these sectors it requires a scalable and low carbon production method that can only be achieved with the use of natural gas.

6.2 Heat Sector Transition

Figure 14 demonstrates the variety of technologies that contribute to the decarbonisation of the heat sector towards 2050. The chart splits the heat sector into non-process and process heating. Non-process includes space and water heating in all buildings, whilst process heating is used for industrial processes in several industries (e.g. metal, glass, plastics, rubber and ceramics production).

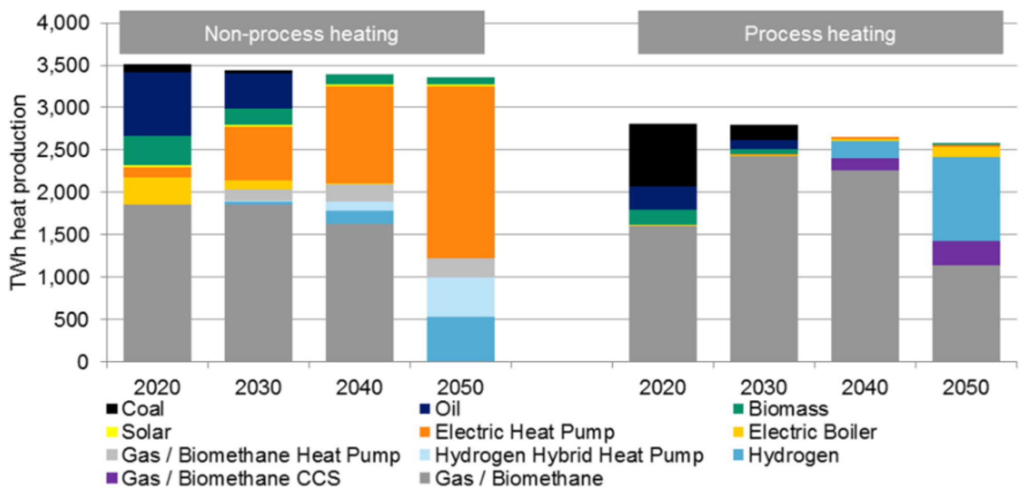

Figure 14 Europe's heat sector under the 'Zero Carbon Hydrogen' pathway (TWh)[5]

In the non-process heat segment, a combination of heat pumps and hydrogen boilers is deployed in the transition to a fully decarbonised sector. While heat pumps offer very high efficiency in providing heat, several considerations can make their use impractical, including:

- extremely cold weather (efficiencies of heat pumps can drop dramatically when temperatures reach very low levels, such as -10° or lower);
- poor insulation (heat pump efficiencies rely on very well insulated properties, which is not a given in many existing buildings across Europe);
- convenience issues (replacing old systems will mean substantial changes to living spaces, including replacement of radiators, or installation of under-floor heating, since heat provided from heat pumps is less intense).

In those situations where heat pumps are impractical, hydrogen boilers provide a viable alternative, sometimes in hybrid systems together with heat pumps. Hydrogen plays a key role in the process heat segment. Providing very high temperatures with electricity is challenging, which limits the effectiveness of electricity in this sector. Use of natural gas with post combustion CCS is a relatively low-cost option of decarbonising heat in this sector. However, CCS may not be available in many countries for technical, economic or political reasons. Hydrogen is the most economical alternative in the other countries that don't allow the development of CCS.

6.3 Transport Section Transition

The transport sector undergoes a major transformation from oil-based fuels to using a combination of electricity and hydrogen, as shown in Figure 155

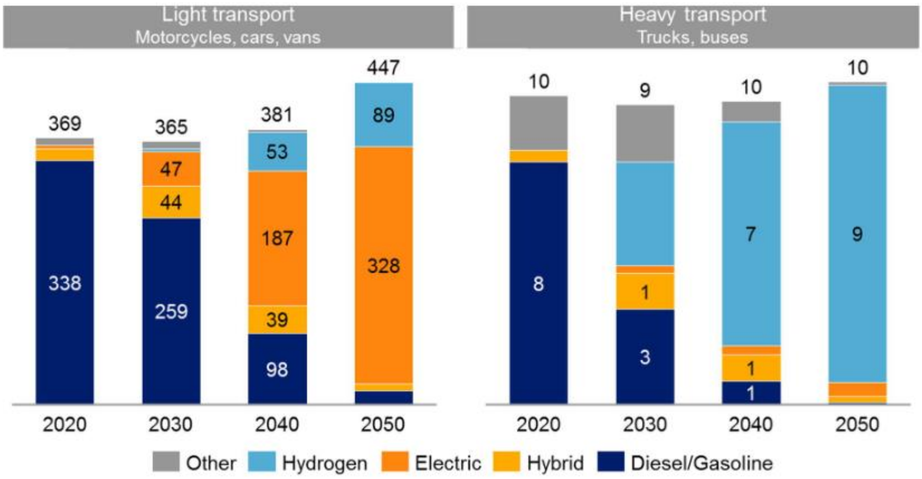

Figure 15 Europe's transport sector under the 'Zero Carbon Hydrogen' pathway (mn vehicles)[5]

In the light transport segment, including motorcycles, cars and vans, battery electric vehicles account for the majority of vehicles on the road in 2050. However, in heavier transport segments, such as trucks and buses, the larger battery sizes that would be required and longer journeys make the use of electric vehicles impractical. In these segments, hydrogen fuel-cell vehicles provide an efficient alternative.

By 2050, hydrogen could also be used to produce synfuels for aviation and maritime transport. In the majority of scenarios, hydrogen and synfuels add up to between 20% and 50% of energy demand in transport in 2050.[19]

6.4 Power Sector Transition

Due to the large increase in the use of electricity in heat and transport, power demand grows from around 3330 TWh in 2020 to around 5000 TWh in 2050. The majority of electricity will be produced by renewables, including 54% from wind, and 18% from solar PV, as shown in Figure 16. Currently, coal, gas and nuclear power plants provide electricity when renewables are not available. After these plants have been decommissioned, there is still a need for similar back up generation. This is provided in part by interconnection flows (within Europe) and flexible hydro generation (most notably in the Nordics), but the system also requires some additional power plants. Where available, natural gas power plants with post combustion CCS (41TWh in 2050) are used, but in countries where CCS is not available, hydrogen CCGTs (192TWh in 2050) fulfil this role.

[19] https://ec.europa.eu/jrc/sites/jrcsh/files/final_insights_into_hydrogen_use_public_version.pdf

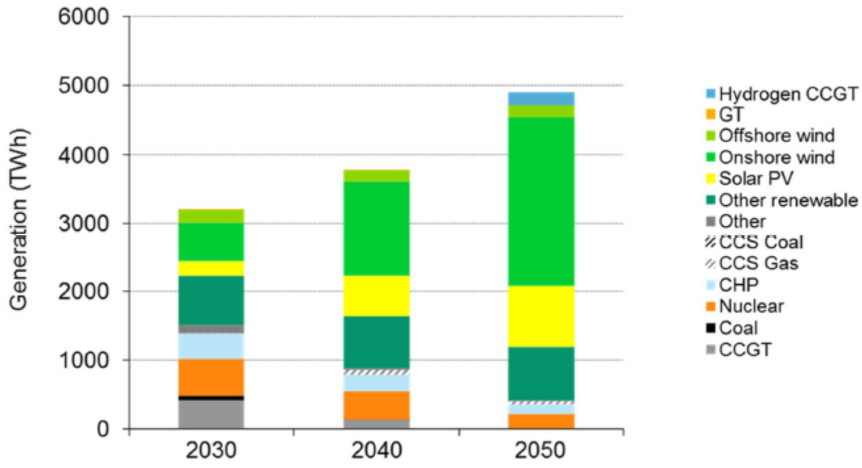

Figure 16 Europe's power generation transformation – 'Zero Carbon Hydrogen' pathway[20]

7. Power to Gas: Ongoing Projects

Power to Gas (P2G) is a term for technologies for converting electrical energy into a gaseous chemical energy carrier.

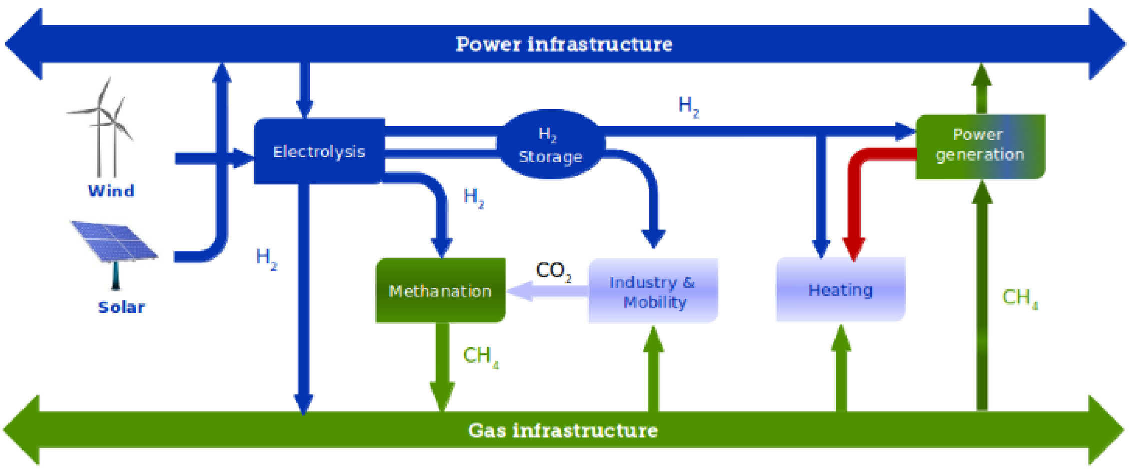

Figure 17 P2G Integration in NG and Electrical Grid

In addition to some demonstration and laboratory projects, about 56 Power to Gas (P2G) plants are currently in operation worldwide, with a tendency to increase installed power in the coming years with a tendency to increase installed power.

[20] Hydrogen from natural gas –The key to deep decarbonisation; Discussion Paper commissioned by Zukunft ERDGAS – July 2019

	Hydrogen-Projects	Methanation-Projects
Feed-in projects	21	36
No. of active projects in 2019	56	38
Installed production capacity	6205 m^3/h	590 m^3/h
	18.6 $MW_{ch,LHV-H2}$	6 $MW_{ch,LHV-CH4}$
Installed electrical load	24.1 MW_{el}	14.5 MW_{el}
Efficiency electricity-to-gas	**77%**	**41%**

Table 2 Status quo of active projects in 2019: Efficiency of the conversion from power togas in projects producing hydrogen or methane (including biological and chemical methanation) and number of projects feeding in their products. Installed electrical load of methanation projects is related to the electrolysis power necessary to feed the methanation unit [21]

In 57 out of 143 projects, the product gas is fed in or is planned to be fed into the natural gas grid and reconverted into electricity or heat or to be used as fuel from there on.

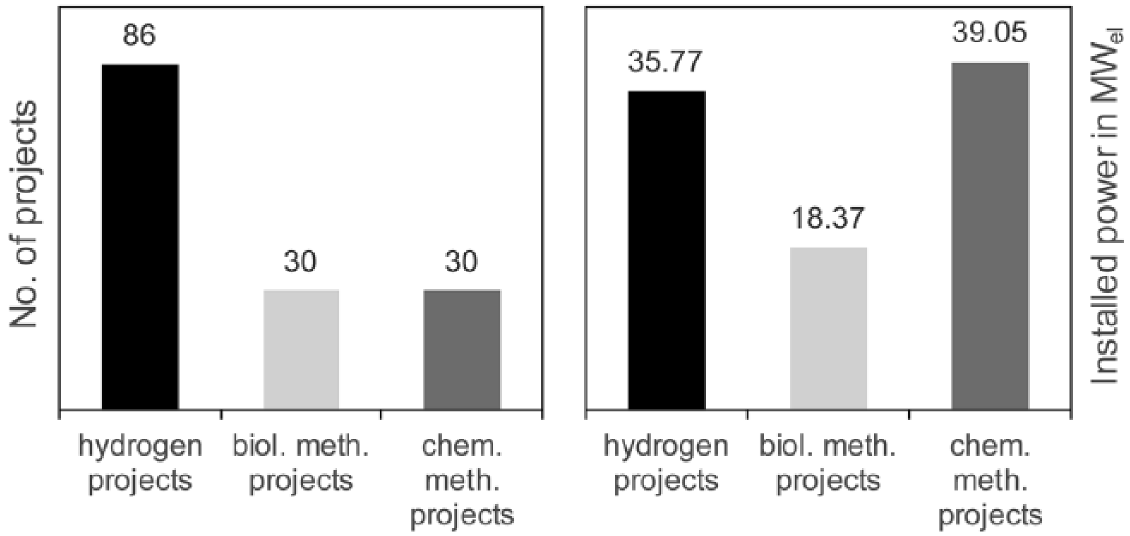

Figure 18 Number of projects (left side) and total of installed electrical power in MWel (right side) of PtG-projects with regard to their products either hydrogen or methane from chemical or biological methanation.

Until early 2019, the main part of P2G power installed, is located in Germany (30.7 MWel) followed by Denmark (2.53 MWel), Canada and the United States of America (both about 0.45 MWel).

Other countries as the Netherlands, France or Hungary are already planning to increase their capacity until 2020 and further on.

[21] Renewable and Sustainable Energy Reviews Volume 112, September 2019, Pages 775-787

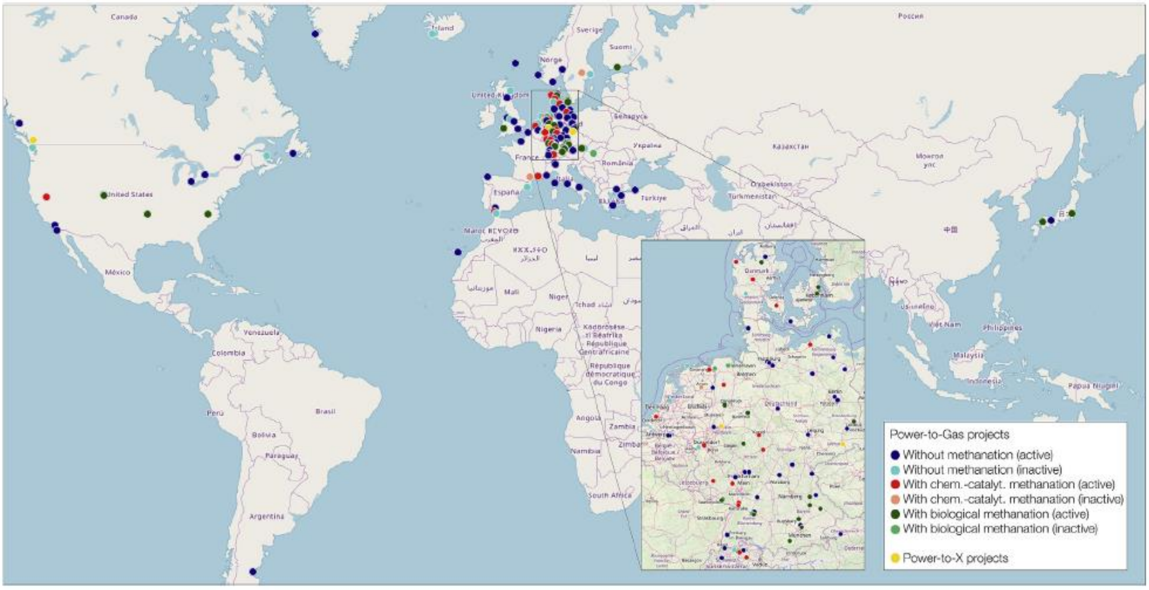

Figure 19 PtG project allocation differentiated according to the target products hydrogen and methane as well as activity/inactivity. Dark green: PtG with biological CO_2-methanation active. Light green: PtG with biological CO_2-methanation inactive. Red: PtG with chemical CO_2-methanation, active. Orange: PtG with chem. CO_2- methanation, inactive. Dark blue: PtG without methanation, active. Light blue: PtG without methanation, inactive. Yellow: Power-to-X.[20]

These projects are intended to demonstrate the effectiveness of P2G technology for balancing the electricity grid, in the face of the randomness of an energy source renewable.

In early 2019, as many as 95 projects were active globally with an electrical power of 38.6 MWel. 58% of them or 56 projects with a total capacity of 24.1 MW_{el}, produce hydrogen. The rest, 38 projects with a total capacity of 14.5 MW_{el}, produce methane.

Product use was further differentiated into local storage and reconversion without gas grid feed-in, fuel production, industrial or substantial use, oxygen and off-heat utilization and research applications.

About 45% of the projects feed in, and 55% store their products locally. Both kinds of product treatment reconvert the gas after buffering. Overall 88% of the projects reconvert their products after either feed into the gas grid or local store.

After reconversion, biofuel production is the most common product utilization phase with application in 29% (36 projects) of all projects. Off-heat gets used in only about 10% of the plants. Use of the products e.g. in industrial processes (4%, 5 projects) and oxygen use (2.4%, 3 projects) only play subordinate roles in application.

Only 13 projects are solely research facilities. This shows, that nearly all of them are designed as technical centres or pilot plants for near-to medium term market application.

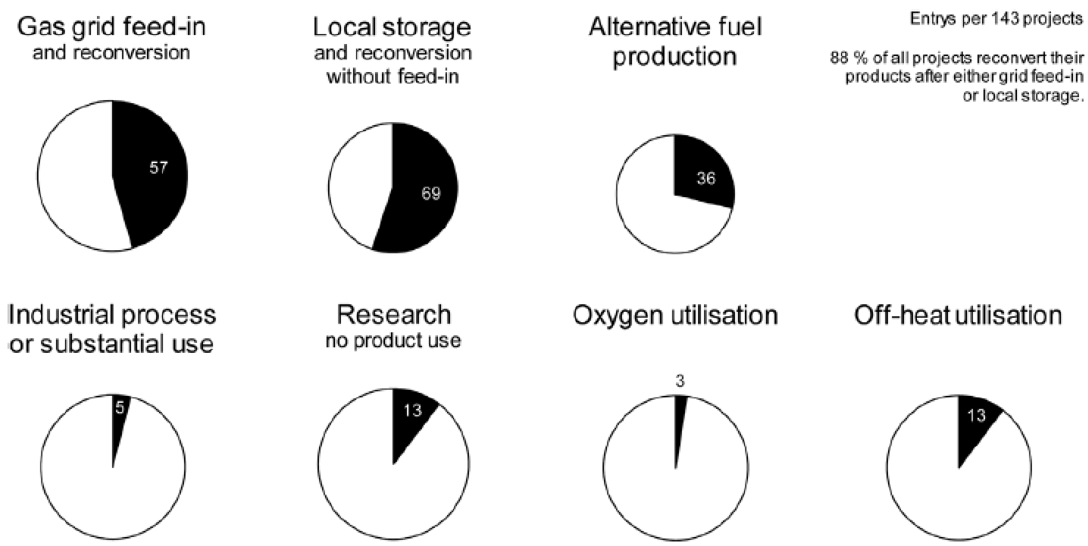

Figure 20 Product gas utilization phases in the different projects.[22]

- Falkenhagen Plant

Figure 21 P2G Plant, Falkenhagen (Germany)

This plant, in operation since 2013, has an installed power of as much as 2 MW and produces an average of 360 Nm^3 of H_2 per hour, from wind power. It is important to note that, despite the high capacity, the plant has a small footprint, which is easy to build, thanks to the compactness and modularity of the electrolysers, and is not visually impactable in any way.

After the power-to-gas plant in Falkenhagen, Brandenburg, was expanded by a methanation stage in May 2018, synthetic natural gas - methane - has recently been fed into the natural gas grid. This allowed the partners of the international research project STORE&GO to demonstrate the technical feasibility of the power-to-gas process through methanation, using electrolysis, for feeding the “green” gas into the natural gas grid. So far, pure hydrogen has been fed into the natural gas grid of the power-to-gas plant in

[22] Renewable and Sustainable Energy Reviews 112 (2019) 775–787

Falkenhagen. Today, the plant produces up to 1,400 cubic meters of synthetic methane (SNG) per day, which corresponds to approximately 14,500 kWh of energy. The methanation is designed for continuous operation and constantly achieves a very high quality of feed. To produce the green methane, the regeneratively produced hydrogen is converted to methane, i.e., synthetic natural gas, with CO_2 in a bioethanol plant. The heat generated during the process is also used by the neighbouring veneer plant.

- Prenzlau Plant

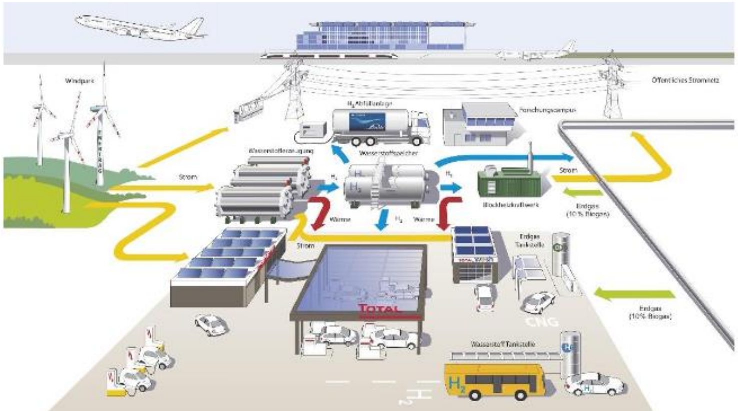

Figure 22 P2G plant, Prenzlau (Germany)

Another example of the integration between electricity, thermal and renewable energy transport uses is the P2G plant in Prenzlau (Germany), which has been in operation since 2012 (Figure 22).

Part of the electricity generated by several wind farms is used to produce hydrogen by water electrolysis, which is then stored and feeds, on demand, both fuel cell car refuelling stations, including a fuel cell Located in Berlin-Brandenburg airport, both a combined electricity and heat production plant for the city's heating network.

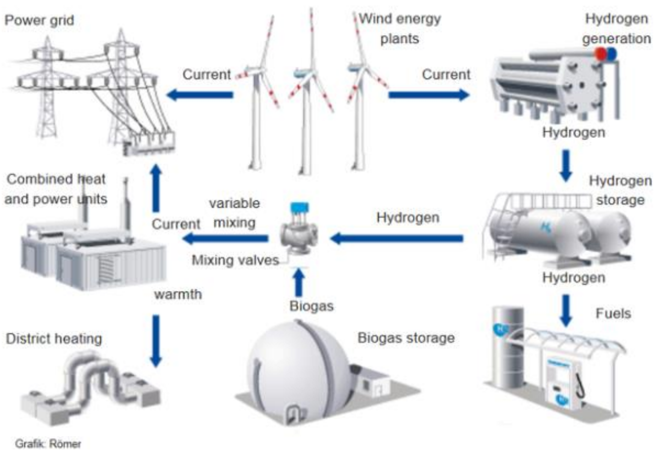

Figure 23 Prenzlau hybrid power plant combining a biogas unit, three wind turbines of 2 MW each, two CHP plants and an electrolysis unit generating hydrogen[23]

[23] Bioenergy RES hybrids − assessment of status in Finland, Austria, Germany, and Denmark; DOI: 10.1002/bbb.2019; Biofuels, Bioprod. Bioref.(2019

- Wertle Plant

Figure 24 Biogas Plant, Wertle

The client for the 6000 kW., plant in Werlte, Lower Saxony (Germany) is the automobile manufacturer Audi AG. The design and construction of the plant was carried out by the plant construction firm ETOGAS GmbH. Commissioning occurred in the fourth quarter of 2013. The plant is designed for the production of electricity-based substitute natural gas for feeding feed into the natural gas grid for use as sustainable fuel for mobility at natural gas filling stations.

The first commercial Power-to-Gas in the world with feed-in of substitute natural gas to the natural gas grid is characterized by a simple basic process plant conception in which no steam is dosed to the educt gas and the dried product gas is fed without further processing steps as replacement gas to the local L-gas grid. Methanation takes place in a molten-salt cooled tube bundle reactor with imposed temperature profile and single passage through the reactor. The temperature control in the hot spot region is implemented in the individual tubes by a step-wise educt gas feed and by the heat transfer medium.

The CO_2 required for the process is separated by mine scrubbing from the biogas of a waste material fermentation plant. Under full load, the P2G plant produces a replacement gas volume flow of around 350 m^3_{stp}/h (without the bio-methane fraction, which is also fed to the gas grid). The feed-in of the replacement gas takes place to the local gas distribution grid. When the capacity of the distribution grid is exhausted (as in the summer, with low gas consumption) feed-in takes place to the transport grid.

Another feature of the 6000 kW plant is the intermediate storage of hydrogen. The hydrogen produced in the alkaline electrolysis with three electrolytic stacks is temporarily stored in a pressurized hydrogen tank at approximately 10 bar. This enables methanation to be temporally decoupled from the intermittent operation of the electrolyser and results in a reduction of the number of start-up and shut-down ramps compared with electrolysis operation.

Audi e-gas is generally produced in two key process steps – electrolysis and methanation. In the first step, renewably generated electricity is used to split water into hydrogen and oxygen. In the second step, the hydrogen is reacted with CO_2 to yield synthetic methane. In the Audi e-gas plant in Werlte in the German state of Lower Saxony, this is done using a chemical-catalytic process under high pressure and high temperature.

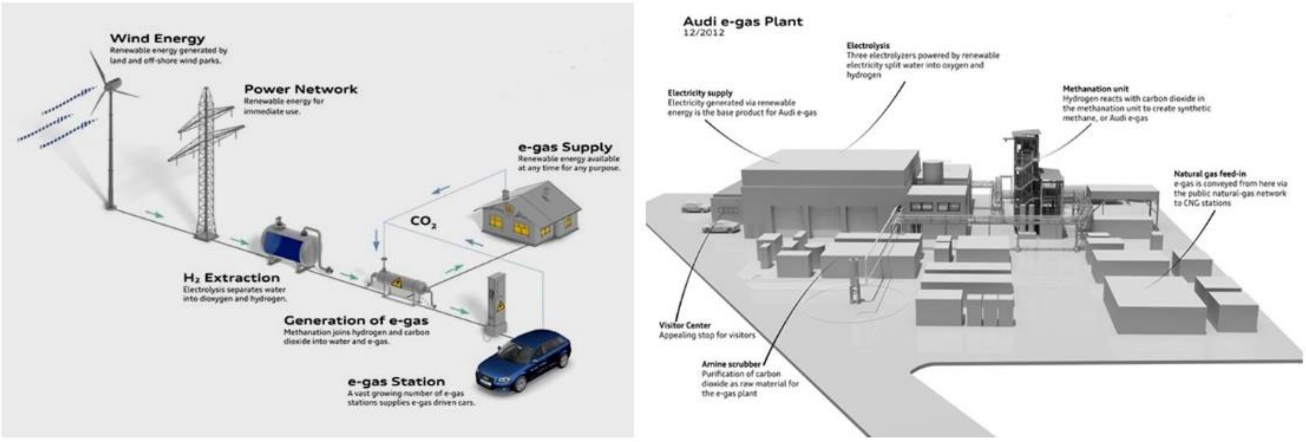

Figure 25 e-gas project: Audi with ETOGAS (ex SolarFuel) and MT-BioMethan [24]

Besides the construction and operation of Power-to-Gas plants in the performance classes 25 kW., and 250 kW_{el}, experimental investigations on the hydrogenation of gases containing carbon oxides are being carried out at ZSW. Specifically. these include the screening of catalysts available on the market, investigations of their deactivation and the processing of product gases from methanation to a replacement gas by means of membrane gas separation technology (downstream membrane gas upgrade). [25]

In the new Viessmann plant, methanation is now purely biological. Highly specialized microorganisms absorb the hydrogen that is dissolved in liquid and the carbon dioxide through their cell walls. From these molecules they then form the new molecule methane. The process is run under a moderate pressure of around five bar and at relatively low temperatures

This first power-to-gas plant utilizes biological methanation across Germany. Its strength lies in the fact that it processes the carbon dioxide contained in the raw biogas directly. Unlike chemical methanation, the CO_2 does not need to be present in high concentration or purified form. This opens up new procurement paths. Smaller sewage treatment and biogas plants, in which no biogas purification is performed, can now come into consideration as CO_2 sources.

The Viessmann Group started up its pilot plant in stages beginning in March 2015. Like the Audi e gas plant in Werlte, it consumes tons of CO_2 in the production of the synthetic gas.

- Approximately 1000 t/year of CH_4 product, seized about 2800 t/year CO_2, 6 MW of Electrolysis
- Residual heat of the methanization process used in an adjacent plant produces biogas.
- Biogas plant, powered by food waste, provides CO_2 for metanation.

[24] www.ravenna2016.it
[25] Natural Gas and Renewable Methane for Powertrains; Springer International Publishing, 2016

➢ SNAM: Contursi Terme Project

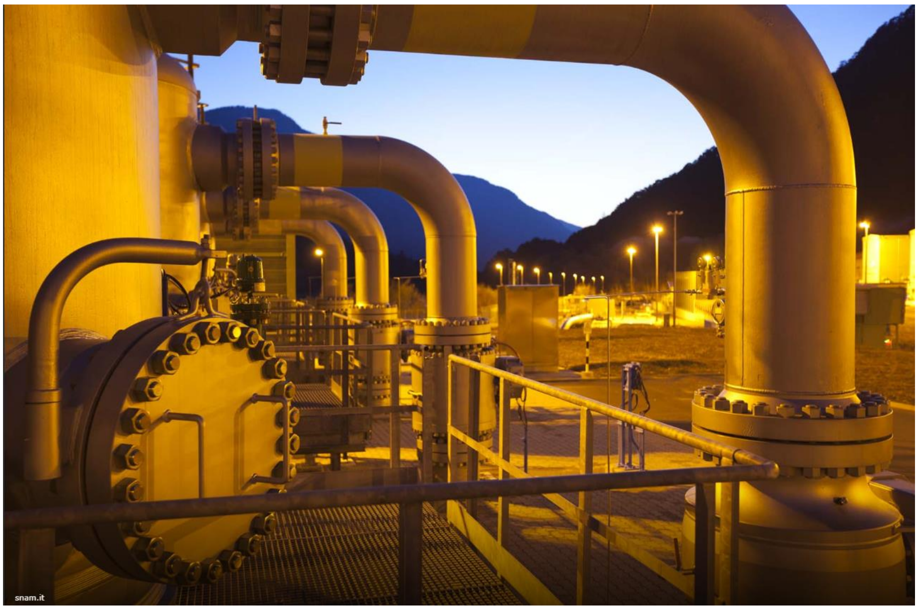

Figure 26 In April 2019, Snam was the first company in Europe to introduce a mix of 5% hydrogen and natural gas in its transmission network.[26]

In April 2019, Snam was the first company in Europe to introduce a mix of 5% hydrogen and natural gas in its transmission network. The trial, which successfully took place in Contursi Terme, in the province of Salerno, involved supplying H_2NG (hydrogen-natural gas mixture) for a month to two industrial companies in the area, a pasta factory and a mineral water bottling company.

By applying the percentage of 5% of hydrogen to the total gas transported annually by Snam, 3.5 billion cubic meters could be added to the network each year, a quantity equivalent to the annual consumption of 1.5 million households which would allow carbon dioxide emissions to be reduced by 2.5 million tons, corresponding to the total emissions of all cars in a city the size of Rome or half of the cars of a region like Campania.

At present, Snam is committed to verifying the full compatibility of its infrastructure with increasing amounts of hydrogen mixed with natural gas, as well as studying hydrogen production from renewable electricity. By the end of the year the experiment will be repeated again on the same part of the network, bringing the amount of hydrogen in the mix supplied to the two companies involved to 10%.[27]

8. The future of Hydrogen: IEA Summary Report

The time is right to tap into hydrogen's potential to play a key role in a clean, secure and affordable energy future. At the request of the government of Japan under its G20 presidency, the International Energy Agency (IEA) has produced this landmark report[28] to analyze the current state of play for hydrogen and to offer guidance on its future development. The report finds that clean hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. It concludes that now is the time to scale up technologies and bring down costs to allow

[26] Snam.it
[27] https://www.snam.it/en/hydrogen_challenge/snam_hydrogen/
[28] https://www.iea.org/reports/the-future-of-hydrogen; 2019

hydrogen to become widely used. The pragmatic and actionable recommendations to governments and industry that are provided will make it possible to take full advantage of this increasing momentum.

- Hydrogen can help tackle various critical energy challenges. It offers ways to decarbonize a range of sectors – including long-haul transport, chemicals, and iron and steel – where it is proving difficult to meaningfully reduce emissions.
- Hydrogen is versatile. Technologies already available today enable hydrogen to produce, store, move and use energy in different ways. A wide variety of fuels are able to produce hydrogen, including renewables, nuclear, natural gas, coal and oil. It can be transported as a gas by pipelines or in liquid form by ships, much like liquefied natural gas (LNG). It can be transformed into electricity and methane to power homes and feed industry, and into fuels for cars, trucks, ships and planes.
- Hydrogen can enable renewables to provide an even greater contribution. Hydrogen is one of the leading options for storing energy from renewables and looks promising to be a lowest-cost option for storing electricity over days, weeks or even months. Hydrogen and hydrogen-based fuels can transport energy from renewables over long distances – from regions with abundant solar and wind resources, such as Australia or Latin America, to energy-hungry cities thousands of kilometers away.

Widespread use of hydrogen in global energy transitions faces several challenges:

- Producing hydrogen from low-carbon energy is costly at the moment. IEA analysis finds that the cost of producing hydrogen from renewable electricity could fall 30% by 2030 as a result of declining costs of renewables and the scaling up of hydrogen production. Fuel cells, refuelling equipment and electrolysers (which produce hydrogen from electricity and water) can all benefit from mass manufacturing.
- The development of hydrogen infrastructure is slow and holding back widespread adoption. Hydrogen prices for consumers are highly dependent on how many refuelling stations there are, how often they are used and how much hydrogen is delivered per day. Tackling this is likely to require planning and coordination that brings together national and local governments, industry and investors.

Regulations currently limit the development of a clean hydrogen industry. Government and industry must work together to ensure existing regulations are not an unnecessary barrier to investment. Trade will benefit from common international standards for the safety of transporting and storing large volumes of hydrogen and for tracing the environmental impacts of different hydrogen supplies.

The IEA has identified four near-term opportunities to boost hydrogen on the path towards its clean, widespread use. Focusing on these real-world springboards could help hydrogen achieve the necessary scale to bring down costs and reduce risks for governments and the private sector. While each opportunity has a distinct purpose, all four also mutually reinforce one another.

- ✓ Make industrial ports the nerve centers for scaling up the use of clean hydrogen. Today, much of the refining and chemicals production that uses hydrogen based on fossil fuels is already concentrated in coastal industrial zones around the world, such as the North Sea in Europe, the Gulf Coast in North America and southeastern China. Encouraging these plants to shift to cleaner hydrogen production would drive down overall costs. These large sources of hydrogen supply can also fuel ships and trucks serving the ports and power other nearby industrial facilities like steel plants.

- ✓ Build on existing infrastructure, such as millions of kilometres of natural gas pipelines. Introducing clean hydrogen to replace just 5% of the volume of countries' natural gas supplies would significantly boost demand for hydrogen and drive down costs.
- ✓ Expand hydrogen in transport through fleets, freight and corridors. Powering highmileage cars, trucks and buses to carry passengers and goods along popular routes can make fuel-cell vehicles more competitive.
- ✓ Launch the hydrogen trade's first international shipping routes. Lessons from the successful growth of the global LNG market can be leveraged. International hydrogen trade needs to start soon if it is to make an impact on the global energy system.

International co-operation is vital to accelerate the growth of versatile, clean hydrogen around the world. If governments work to scale up hydrogen in a co-ordinated way, it can help to spur investments in factories and infrastructure that will bring down costs and enable the sharing of knowledge and best practices. Trade in hydrogen will benefit from common international standards. As the global energy organisation that covers all fuels and all technologies, the IEA will continue to provide rigorous analysis and policy advice to support international co-operation and to conduct effective tracking of progress in the years ahead[29].

9. Conclusion

The most practical and economic pathway to decarbonisation includes hydrogen that is produced mainly from natural gas. Whilst hydrogen produced from electrolysis has a role to play, the essential element to allow delivery of large-scale hydrogen deployment in heat, industry, transportation and power is the inclusion of hydrogen produced from natural gas.

Biological routes for hydrogen are under development and set to impact the hydrogen energy sector. The use of such techniques to produce methane have been development and provide an indirect route to hydrogen. Furthermore, the use of biomass is set to make a significant impact through gasification, pyrolysis and fermentation. Current technology that produces alcohols, mainly ethanol, by fermentation could also be seen as a route to hydrogen, by for example electro-reforming.

Overall there is a significant number of options and technologies for hydrogen production that are potentially sustainable and avoid this use of fossil fuels. However, their development requires significant R&D and notably large investments in plant as well as motivation driven by political legislation.

Existing transmission networks can continue to transport natural gas to demand centres allowing hydrogen to be produced close to demand and thus minimising network conversion. This will also enable natural gas with post-combustion CCS to be used in industry and power generation. This will allow a more efficient use of natural gas and hydrogen and the existing networks.

Existing supply routes and markets for natural gas can continue to operate, providing efficient and competitive markets and ensuring security of supply, as they have done in the past.

Much will need to be done to secure a hydrogen based future including advances in technology, the development of a hydrogen supply chain and public acceptance.

[29] https://www.iea.org/reports/the-future-of-hydrogen

Policy will play a key role in advancing the hydrogen economy and has a significant role in achieving decarbonisation. Specifically, it must enable industries to make the investments and adaptations necessary in order to develop a hydrogen energy economy. Accordingly, European and national policy makers will need to recognise the importance of hydrogen from natural gas in decarbonisation efforts and consider the following.

- Policies that support the role of hydrogen in decarbonisation efforts and allow different technologies (including zero carbon gas) to compete on an equal basis should be developed to achieve the most efficient outcome.
- Targets for zero carbon gas in the European energy mix should be set (including renewable gas from bio-sources and decarbonised gas), in order for investment in zero carbon gas options to become attractive and for innovation to progress.
- Research into implementation of hydrogen technologies should be supported. These include fuel cells, hydrogen-based fuels and methane pyrolysis methods, as well as uses for end use carbon products.
- Investments in energy networks should be considered based on the impact of the investment on decarbonisation. The role of hydrogen from natural gas and the role of existing gas networks in enabling decarbonisation should be recognised, and research into converting natural gas networks to hydrogen should be supported.

In a future where zero carbon hydrogen is produced from natural gas, the gas wholesale market could continue to operate in a similar way to today. Instead of gas being used predominantly as an end use fuel, it would become mainly a feedstock for zero carbon hydrogen. As different companies (for example utilities, industrial users) could produce hydrogen there would continue to be many different buyers on the wholesale market, as there are today. The supply of natural gas would be largely unchanged. European buyers of natural gas would continue to benefit from the competition between indigenous production, pipeline imports and LNG as they do today. As gas demand would remain significant the market would be of sufficient size to enable liquid trading as well as being attractive to natural gas producers from abroad.