Hydrogen - a carbon-free energy carrier and commodity

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Contents

Abstract

Hydrogen like electricity, is a carbon-free energy carrier. These two energy carriers will become the main energy carriers in the future sustainable energy system. Renewable energy resources are unevenly distributed over the world. In an energy system based on renewable energy resources hydrogen will be the energy carrier that can be cost efficiently transported and stored to deliver renewable energy from good remote resource areas, at the right time and place to the energy demand. Next to this systemic role, hydrogen is also important to decarbonize the energy use in hard to abate sectors in industry, mobility, electricity balancing and heating. However, cost competition between imported renewable hydrogen and locally produced renewable hydrogen and electricity will become apparent over time. Hydrogen will become the zero-carbon energy carrier and commodity that will be traded globally.

Hydrogen infrastructure can be realized by re-purposing the gas infrastructure, pipelines, and salt cavern storage, without major adaptations. And hydrogen can be shipped around the world. Future hydrogen systems will therefore have similar characteristics as present-day natural gas systems.

During an intermediate period, natural gas can be converted at the source into hydrogen without any CO_2 emissions (no-carbon fossil hydrogen). This makes a fast transition towards hydrogen as energy carrier and commodity possible. Over time more and more hydrogen from solar and wind can be fed into the system, eventually replacing fully the no-carbon fossil hydrogen. Such a system approach can establish a fast, cheap, reliable, secure, and inclusive transition to a sustainable energy system.

1. Introduction

The role of hydrogen in realizing a fully renewable energy systems is recognized all around the world. Until the first half of 2021 over 30 countries have implemented hydrogen strategies and the vast majority of these strategies have been implemented in 2020. Among others, the countries that published such strategies are Japan, South Korea, Australia, Chili, Morocco, China, Russia, Saudi Arabia, Austria, France, Germany, the Netherlands, Norway, Portugal, and Spain.

In Europe on 8 July 2020 the European Commission released the EU Hydrogen Strategy for a Climate Neutral Europe as part of their European Green Deal. The strategy defines a target of 1 million tonnes of clean hydrogen per year and an electrolyser capacity of 6GW by 2024, growing to 10 million tonnes per year with at least 40GW electrolyser capacity by 2030. It also recognises the importance of hydrogen import from neighbouring regions, especially North Africa (EuropeanCommission, 2020).

The main goals of the current hydrogen strategies are: reduction of greenhouse gas emissions, especially in hard to abate sectors; diversification of energy supply; integration of renewables; foster of economic growth; support national technology developments; security of supply and strategic reserves and, last but not least, develop of hydrogen for export and import (LudwigBölkowSystemtechnik, 2020).

But why is there so much interest in hydrogen by governments and companies? How can hydrogen be produced, transported, stored? Where will hydrogen be used? Which technology, economic and system developments are the drivers for hydrogen as an energy carrier and commodity? And what will be the role and characteristics of hydrogen in the future renewable energy system? These issues will be analysed and discussed in this paper.

2. Hydrogen production and use

2.1 Hydrogen Production Technologies

Hydrogen, like electricity, is a carbon-free energy carrier, which means that no CO_2 emissions are released into the atmosphere when hydrogen is burned or converted. The only 'waste' product is pure water. However, just like electricity, it does not mean that the production of hydrogen is without (life cycle) CO_2 emissions. Hydrogen needs to be produced from a molecule that contains hydrogen with a conversion technology that requires energy input.

Hydrogen can be produced from fossil fuels (hydrogen-carbon molecules) from biomass resources (hydrogen-oxygen-carbon molecules) or from water (hydrogen-oxygen molecule).

When fossil fuels or biomass are the source of hydrogen, the input energy comes from the fossil fuels or biomass. However, when water is used as the source of hydrogen, the input energy could come from electricity (electrolysis process) heat (thermolysis process) or solar light-photons (photolysis or photo-electrochemical process)

In the end, the energy source together with the conversion process, input energy and flue gas treatment processes determine whether or not direct or indirect CO_2 emissions to the air will take place. An overview of the most relevant hydrogen production technologies with their present maturity level, main output products and the related CO_2 emission to the air, expressed in a 'colour' are summarized in table 1 (van Wijk, 2021). It is humorous to describe a colourless gas with a colour, while the colour of hydrogen may give an indication of the CO_2 emissions to the air, it is not a precise definition of the amount of CO_2 emissions to the air, it only gives an idea.

A common opinion is that renewable or green hydrogen, without CO_2 emissions to the air, can only be produced by water electrolysis using renewable electricity, whereby renewable electricity is most often seen as only solar and wind electricity, although hydropower and geothermal electricity will play a role in certain areas too. From this table it is obvious that by using biogenic waste also renewable or green hydrogen can be produced. When the CO_2 from these processes is captured and used or stored, hydrogen from biogenic waste could even have negative CO_2 emissions to the air.

A new technology development is the photo-electrochemical cell, whereby sunlight (photon) directly splits a water molecule into hydrogen and oxygen. It implies that no separate electrolysis process will be necessary. Many universities around the world do research to optimize this process, higher efficiencies, less and cheaper material use, less degradation, and a stable process. However, Repsol, a Spanish oil company, has announced in August 2021 that 'direct solar-to-hydrogen', without need for electrolysis as intermediate step, will be commercially viable by 2030 (Radowitz, 2021).

Even hydrogen production from fossil fuels could have zero CO_2 emissions to the air. Present hydrogen production from natural gas is with SMR (Steam Methane Reforming) plants. In the future, also ATR, (Auto Thermal Reforming) plants will be installed. These reforming processes produce two different CO_2 flows; (i) a pure CO_2 flow from the reforming process and (ii) a flue gas flow also containing CO_2 from burning natural gas to produce heat for the process. It is relatively easy to capture 50% (SMR) up to 100% (ATR) of the pure CO_2 flow from the reforming process. However, separating the CO_2 from the other elements in the flue gas is more difficult and consequently more costly. Therefore, present day believe is that you can only capture and store up to 90% of the CO_2 at ATR plants. however, if part of the produced hydrogen is burned to produce the process heat, there is only steam as flue gas without CO_2, which implies that even up to 100% of the total CO_2 could be captured and stored.

With a new technology, methane pyrolysis, methane (CH_4) is split into hydrogen (H_2) and solid carbon (C). This process does not produce CO_2 at all, it will depend on the inputted energy into heat whether or not indirect CO2 emissions take place. If part of the produced hydrogen and/or electricity from renewable or nuclear resources is used, the production of hydrogen is without any CO_2 emissions and with this technology CO_2 capture and storage is not necessary.

Source	Process/Technology	Maturity	Main output	Colour of hydrogen
Natural gas	Steam methane reforming (SMR) Auto-thermal reforming (ATR) Methane Pyrolysis	Mature Mature First plant 2025	$H_2 + CO_2$ $H_2 + CO_2$ $H_2 + C$	**Grey** or **blue**, depending on the capture technology and the process input energy 50-100% of CO_2 can be captured and stored. With ATR using part of the produced H_2 as energy for process heat, 100% CO_2 emission capture and storage is possible **Turquoise**, indirect CO_2 emissions are zero if green electricity or part of the produced hydrogen is used as process energy
Coal	Partial Oxidation/Gasification Underground coal gasification	Mature Projects exist	$H_2 + CO_2 + C$ $H_2 + CO_2$	**Brown** or **blue**, depending on the CCS technology 50-90% of CO_2 can be captured and stored.
Solid Biomass, Biogenic waste	Gasification Plasma gasification	Near Maturity First Plant 2023	$H_2 + CO_2 + C$ $H_2 + CO_2$	**Green** Negative CO_2 emissions possible
Wet Biomass, Biogenic waste	Super critical water gasification Microbial Electrolysis Cell	First Plant 2023 Laboratory	$H_2 + CH_4 + CO_2$ $H_2 + CH_4$	**Green** Negative CO_2 emissions possible
Electricity + water	Electrolysis Alkaline PEM SOEC	 Mature Near Maturity Pilot Plants	 $H_2 + O_2$ $H_2 + O_2$ $H_2 + O_2$	All shades of **grey** to **green** and **pink** depending on the source for electricity production. With electricity from renewable resources, **green H_2** and from nuclear, **pink H_2** is produced, both with zero CO_2 emissions
Sunlight + water	Photoelectrochemical	Laboratory	$H_2 + O_2$	**Green**

Table 1: Hydrogen production processes, their maturity status, main output molecules and their 'colour', (*adopted and modified from (van Wijk, 2021))*

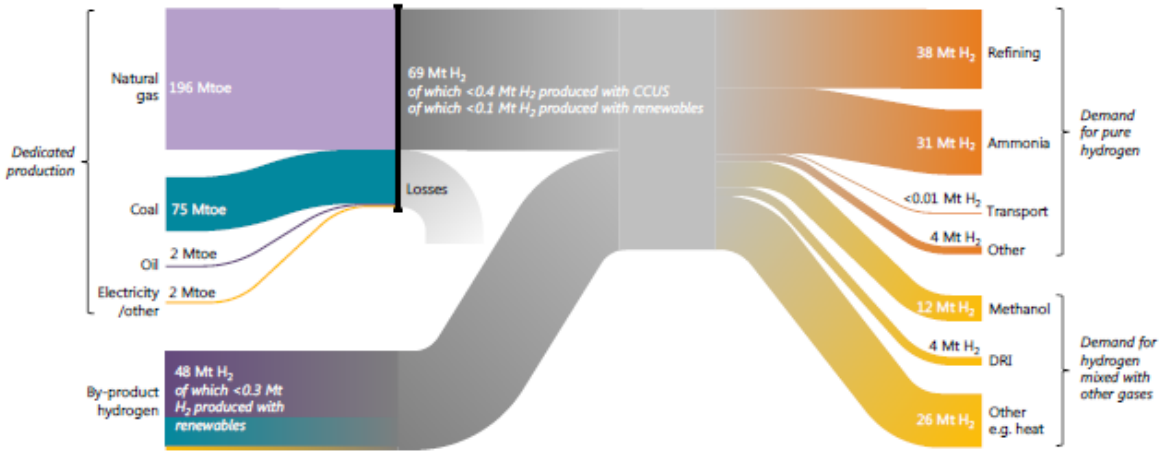
2.2. Present hydrogen use

Today, hydrogen is mainly produced from natural gas and coal and currently it is primarily used as a feedstock to produce chemical products, ammonia (the main component of fertilizers) and methanol. Hydrogen is also used in refineries to desulfurize oil and in the production of kerosine, gasoline and diesel. The primary energy input by gas and coal for hydrogen production is about 3.200 TWh, representing roughly 2% of world-wide primary energy consumption. Figure 1 presents the energy balance for worldwide hydrogen production and consumption (IEA, 2019).

Today, almost all hydrogen is produced and used at or nearby chemical and petrochemical sites. Natural gas is transported by pipeline and coal by ship, rail, or truck to the location of the refinery, fertilizer, or methanol plant where gas or coal is converted into hydrogen. The hydrogen is therefore produced and used at the same location which is called captive hydrogen production and use. There is a limited, privately owned hydrogen pipeline infrastructure at chemical sites, especially to secure reliable baseload supply. There is no public infrastructure, no public market, and no market regulation for hydrogen.

Hydrogen at present is not used as an energy carrier and hydrogen as such is not used in the public domain for heating buildings and only to a very limited extent for transport. Hydrogen is absent or only beginning to be considered as an energy carrier within energy law and energy regulations.

Although hydrogen in its pure form is almost absent in the public domain energy system of today, it is not absent in a mixed form. Town or city gas, produced from coal or oil, was a synthetic gas distributed in cities for cooking and heating. This town gas composition is for more than 50% hydrogen. Natural gas has replaced town gas since the 1970s-1980s in many places around the world. However, especially in China (Hong Kong and 20 other Chinese provinces), town gas produced from naphtha and natural gas, with over 50% hydrogen and the rest mainly methane as town gas composition, is still used for heating and cooking (TownGasChina, 2021).



Notes: Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. Other forms of demand for hydrogen mixed with other gases (e.g. carbon monoxide) include the generation of heat from steel works arising gases and by-product gases from steam crackers. The shares of hydrogen production based on renewables are calculated using the share of renewable electricity in global electricity generation. The share of dedicated hydrogen produced with CCUS is estimated based on existing installations with permanent geological storage, assuming an 85% utilisation rate. Several estimates are made as to the shares of by-products and dedicated generation in various end uses, while input energy for by-product production is assumed equal to energy content of hydrogen produced without further allocation. All figures shown are estimates for 2018. The thickness of the lines in the Sankey diagram are sized according to energy contents of the flows depicted.

Source: IEA 2019. All rights reserved.

Figure 1: Energy Balance for worldwide hydrogen production and consumption 2018 (IEA, 2019)

2.3. Hydrogen application technologies

In a transitional period, hydrogen can be used by combustion in a boiler, furnace, engine, or turbine, to produce heat, electricity, or mechanical power. However, in the future, electrochemical conversion via fuel cells will become more important. The fuel cell reaction is the reverse of the electrolyser reaction. Fuel cells systems have been developed over the past years especially by car manufactures for drive trains in all kinds of mobility. Fuel cells have a similar technology structure as electrolysers, batteries, or solar: it is cells, stacked together, whereby stacks are built together with other equipment to a fuel cell system. R&D is of course important to bring down cost, increase efficiencies, reduce degeneration, and bring down the amount of materials, especially platinum. In particular, fuel cell and stack mass production will drive down cost drastically. Mass production of cells and stacks (plants that produces 500.000 fuel cell systems per year) will bring down fuel cell system Capex cost for cars to $ 30-40/kW (Thompson, James, & all, 2018). Fuel cell capex cost will be lower and conversion efficiencies are higher than for present day combustion technologies, such as engines or turbines. Therefore, in future, fuel cell technology will be at least cost competitive, but in most cases cheaper then present-day combustion technology.

2.4. Fuel cell systems will be applied in all sectors

Fuel cell systems are developed by car manufacturers as drive trains in fuel cell electric vehicles. However, these fuel cell systems can be applied in other mean of transport such as ships, trains, drones, and planes. Besides these applications in mobility, fuel cell systems will play a crucial role in other applications as fuel cells that produce electricity and heat will be used in houses and buildings. The volume and temperature level of the heat can be brought to the desired level by using heat pumps. Next to producing heat, the produced electricity from the fuel cells supplements the electricity from solar panels on the roof. Panasonic in Japan has introduced a small scale (< 1 kWe) fuel cell home system, that can be connected to the natural gas grid, the natural gas is reformed to hydrogen by a small reformer on top of the fuel cell (FuelCellsWork, 2020). Already a couple of 100.000 of these systems are sold in Japan.

Fuel cells systems can be used as electricity balancing plants, producing electricity when renewable sources cannot meet the demand. These fuel cell systems can be installed very de-centralized in villages, neighbourhoods and at office sites, producing electricity and heat locally.

3. Hydrogen cost

3.1. Hydrogen production cost

3.1.1. Hydrogen production cost from natural gas

Many studies have analysed hydrogen production cost, amongst others the IEA (IEA, 2019), Bloomberg-NEF (BloombergNEF, 2020), and the Hydrogen Council (HydrogenCouncil, 2020). In general, for all mature hydrogen production technologies, the energy cost is the most important factor in the hydrogen production cost. The IEA analysed the production cost of hydrogen from natural gas in several parts of the world (IEA, 2019): it is lowest in regions with low gas prices, the Middle East, the Russian Federation and North America and highest in gas importing countries such as Japan, Korea, China, and India. Gas prices vary between 3-11 $ per million Btu (0.010-0.038 $/kWh) with fuel costs the largest cost component accounting for between 45% and 75%. The hydrogen production cost by SMR from natural gas vary between 0.9 to 1.8 $/kg H_2

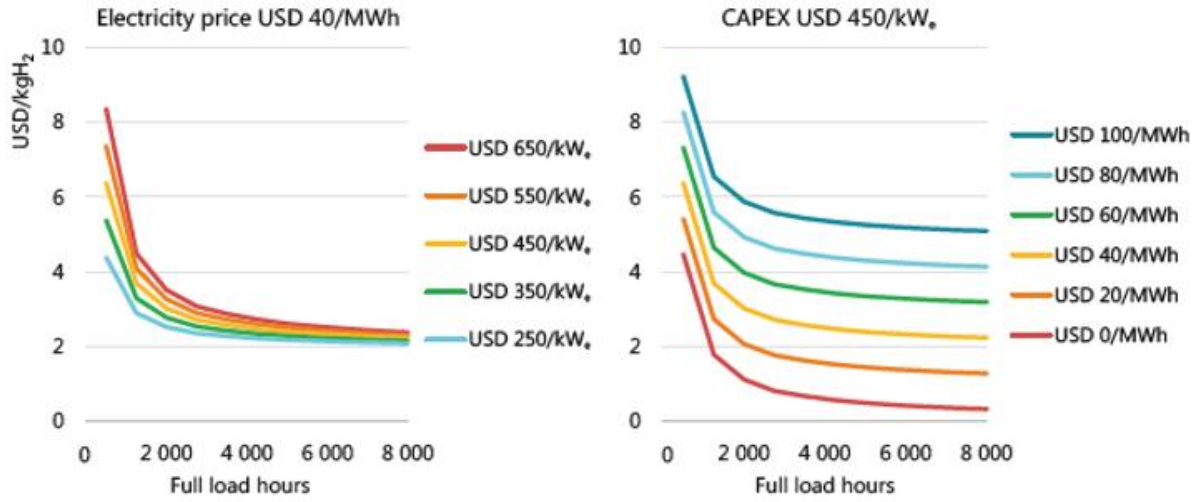
The hydrogen production cost by SMR with carbon capture and storage (CCS) are also calculated by the IEA. The results show that CCS adds about 1 $/kg H_2 to the hydrogen production cost. If a carbon

tax is added to the hydrogen production cost from natural gas by SMR, every 10 dollar per ton CO2 price adds about 0.1 $/kg to the hydrogen price.

3.1.2. Hydrogen production cost by water electrolysis with renewable electricity

The hydrogen production cost by water electrolysis is also dominated by the energy cost. The IEA has analysed the hydrogen cost as a function of full load hours for different electrolyser investment cost and electricity cost. Figure 2 shows clearly that the electricity cost is the most dominant factor in the hydrogen production cost. As a rule of thumb every 10 $ per MWh (0.01 $/kWh) with an electrolyser efficiency of 80% HHV (67% LHV) adds to the cost 0.5 $/kg H_2. Of course, the electrolyser Capex and Opex cost at low full load hours, which is the case for solar, contributes also to the hydrogen production cost. As an example, the hydrogen production cost from solar electricity cost of 0.01 $/kWh, electrolyser Capex of 250 $/kW, 2,000 full load hours and a 3% WACC, are about 1 $/kg H_2. In this case, the electricity cost and the Capex + Opex contributes both 50% to the total hydrogen production cost.

At good renewable resources sites (10-20 $/MWh electricity cost), low-cost green hydrogen can be produced that can compete around 2030 with present day fossil grey hydrogen cost (1-1.5 $/kg) and in the long run with electricity cost below 10 $/MWh even with natural gas. Of course, electrolyser Capex and Opex cost reductions are important, but electricity cost is the dominant cost factor. With a conversion efficiency of 50 kWh/kg H2, every cent per kWh electricity cost (=every 10 $/MWh) adds 0.5 $/kg cost to the total hydrogen cost (BloombergNEF, 2020) (HydrogenCouncil & McKinsey, 2021).



Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

Source: IEA 2019. All rights reserved.

Figure 2: Levelized cost of hydrogen production as a function of full load hours for different electrolyser investment costs (left) and electricity cost (right) (IEA, 2019)

3.1.3. Electrolyser technology cost come down by mass production, technology integration and multi-GW-scale projects

Alkaline electrolyser technology is a hundred year old technology, today in use for chlorine production from dissolved salt (NaCl) in water, with hydrogen as a by-product. The worldwide installed capacity of alkaline electrolysers is roughly 20 GW. These alkaline electrolysers can be easily adapted for hydrogen production, while also new electrolyser technologies, such as PEMEL and SOEC are in development. It is an electrochemical conversion technology, with a similar technology structure as Solar PV or batteries. Electrolysers are built up from electrolyser cells, cells are stacked onto each other to a stack (called a module for Solar PV), with capacities of 0.1-5 MW). For GW electrolysers

numerous stacks are installed, reducing the balance of plant cost per kW installed. Technology improvements by R&D are important to bring down costs, but especially mass production of cells and stacks, system integration with solar and wind and multi-GW renewable hydrogen production plants, will bring down the Capex and Opex cost. These multi-GW renewable hydrogen production plants are connected to the solar and/or wind turbines and not to an electricity grid (van Wijk & Chatzimarkakis, 2020).

If a comparison is made between hydrogen production from natural gas and hydrogen production from solar PV electricity, a similar cost structure is seen. Natural gas cost of 3 million BTU (0,01 dollar per kWh) contributes about 0.5 dollar/kg H_2 which is the same for electricity cost of 0.01 dollar per kWh. SMR Capex cost, estimated by IEA, are between 500 and 900 dollar per kW and with 8.000 full load hours it contributes also about 0.5 dollar/kg H_2. This equals the Capex cost of 250 dollar/kW for electrolysers with 2,000 full load hours, which is the case for solar at good resource locations.

3.2. Hydrogen transport cost

Hydrogen can be transported over large distances by pipeline or ship, which makes it possible to transport hydrogen worldwide. The cost for both transport modes will be discussed below.

3.2.1. Hydrogen transport cost by pipeline

Hydrogen transport by pipeline is already common practice for decades. For instance, Air Liquide operates a hydrogen pipeline infrastructure for many decades from the Netherlands, throughout Belgium, to the North of France. Existing natural gas pipeline infrastructure could also be re-used for hydrogen transport, both the large transport steel pipelines as the distribution PE or PVC pipelines could be relatively easy and cheap re-used for hydrogen transport, as shown by several studies from gas TSO's (GasforClimate, 2020) (GasforClimate, 2021), KIWA (Kiwa, 2018), DNV-GL (DNV-GL, 2017) and others.

A group of European gas infrastructure companies from 21 countries have presented in April 2021 their roadmap to realize a dedicated European Hydrogen Backbone, see figure 3. A hydrogen backbone (based on converted 20, 36 and 48 inch gas pipelines) can transport respectively 2 GW, 5 GW and 15 GW hydrogen (HHV) per pipeline (GasforClimate, 2021). Their estimate is that the transportation cost of a European hydrogen backbone, consisting of 75% converted gas pipelines and 25% new hydrogen pipelines, with 5,000 full load operating hours per year will be about €0.16 /kgH_2/1000km. However, building new large, dedicated pipelines and transporting base-load hydrogen at 80 bar could reduce transport costs even below €0.1/kgH_2/1000km (GasforClimate, 2021).

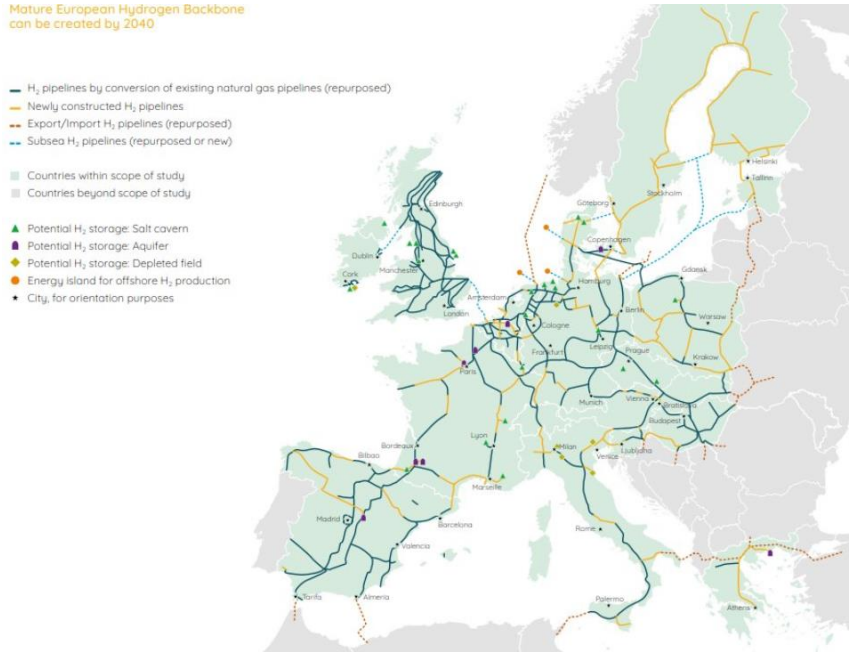


Figure 3: European Hydrogen Backbone 2040, about 40,000 km hydrogen pipelines, 70% retrofitted gas pipelines and 30% new constructed hydrogen pipelines (GasforClimate, 2021)

Hydrogen transport by pipeline over distances of a couple of 1,000 km is a cost-effective way to transport energy. In comparison with electricity transport over these distances, hydrogen transport is roughly a factor of 10 cheaper. In a study for the US-DOE, the cost for energy transport of natural gas, hydrogen, oil, methanol, ethanol, and electricity have been compared. The results are shown in figure 4 (James, DeSantis, Huya-Kouadio, Houchins, & Saur, 2018). They estimate the hydrogen transport cost by pipeline at 5 $/MWh/1000 miles, which is equivalent to €0.1/kgH_2/1000km.

The capacity for a HVDC transport cable is considerably lower than for liquid or gaseous molecule transport through a pipeline. Additionally, energy losses at electricity transport are considerable due to the resistance in the cable. For molecule transport there are no molecule losses, although due to the pressure drop over the pipeline compression energy is needed, see figure 4. In the US-DOE study, the flow speed for hydrogen is kept the same as for natural gas, which shows a factor 8 lower cost for hydrogen transport compared to electricity transport.

Electricity transport cost can be further reduced by increasing voltage levels and therefore reducing losses. However, hydrogen cost could be further reduced by increasing the hydrogen flow speed and increasing pressure levels in the pipeline. So, also in the future the transport cost for electricity will be about a factor of 10 more expensive than hydrogen transport by pipeline.

(Relatively) Low-Capacity drives electrical transmission costs up.

Liquids have high energy densities and low pumping costs

	Electrical	Liquid Pipeline			Gas Pipeline	
Energy Carrier	HVDC	Crude Oil	Methanol	Ethanol	Nat Gas	Hydrogen
Flow (amps,kg/s)	6,000	1,969	1,863	1,859	368.9	69.54
Rated Capacity (MW)	2,656	91,941	37,435	50,116	17,391	8,360
Capital Cost ($M/mile)	$3.9M	$1.47M	$1.92M	$1.92M	$1.69M	$1.38M
Operating Power: Rated Capacity	12.9%	0.78%	2.02%	1.51%	2.67%	1.94%
Capital Cost ($/(mile-MW))	$1,467	$16	$51	$38	$97	$166
Transmission Cost ($/MWh/1000mi)	$41.50	$0.77	$2.2	$1.7	$3.7	$5.0

Electrical transmission faces high cost for sending electricity

Figure 4: Transmission cost comparison between electricity transport cables, liquids, and gases through pipelines (James, DeSantis, Huya-Kouadio, Houchins, & Saur, 2018).

3.2.2. Hydrogen transport cost by ship

Hydrogen transport by ship makes it possible to transport hydrogen worldwide. Hydrogen can be transported by ship as liquid hydrogen, by converting it to ammonia (NH3) or by binding the hydrogen to a liquid organic hydrogen carrier (LOHC). All three have different characteristics and advantages. Liquid hydrogen transport has the advantage that it can be transported by ship at sea and truck on land to refuelling stations. Liquid hydrogen transport by truck can carry 4-10 times as much hydrogen as compressed hydrogen transport by truck and, hence, it is cheaper. However, liquid hydrogen transport by ship is new: Those carriers have to be developed and build. Ammonia transport by ship is a mature technology with a mature supply chain and in use by the fertilizer and chemical industry. Ammonia can be used in diesel engines to replace diesel. It can be transported inland by pipelines (ammonia pipeline infrastructure existing in the US) or by ship, rail or truck and can be cracked back to hydrogen. LOHC can be transported by existing oil tankers and stored in oil tanks and can therefore re-use existing oil assets. The LOHC's can be transported inland by pipeline, ship, rail, or truck. Dehydrogenation can be done in port areas or at the use sites, whereby the carrier has to be transported back. Several ports are developing hydrogen import and export facilities and strategies. For instance, the port of Rotterdam in the Netherlands has developed a hydrogen strategy, in which they foresee a hydrogen throughput of 20 million tonnes (788 TWh $_{(HHV)}$) hydrogen in 2050 (PortofRotterdam, 2020).

Although difficult, a comparison has been made between the three different shipment modes to transport hydrogen from Saudi Arabia to the Netherlands to supply hydrogen fuelling stations, see figure 5 (HydrogenCouncil, 2020). The cost for the three different will depend on distance and especially on the hydrogen end use, which modality will be the most cost effective. It is expected that at present ammonia shipment supply chain cost will be the lowest because this is already a mature and well-established supply chain. However, in the future, liquid hydrogen and LOHC shipment supply chain cost is expected to come down, due to technology improvements and scaling up of hydrogen volumes.

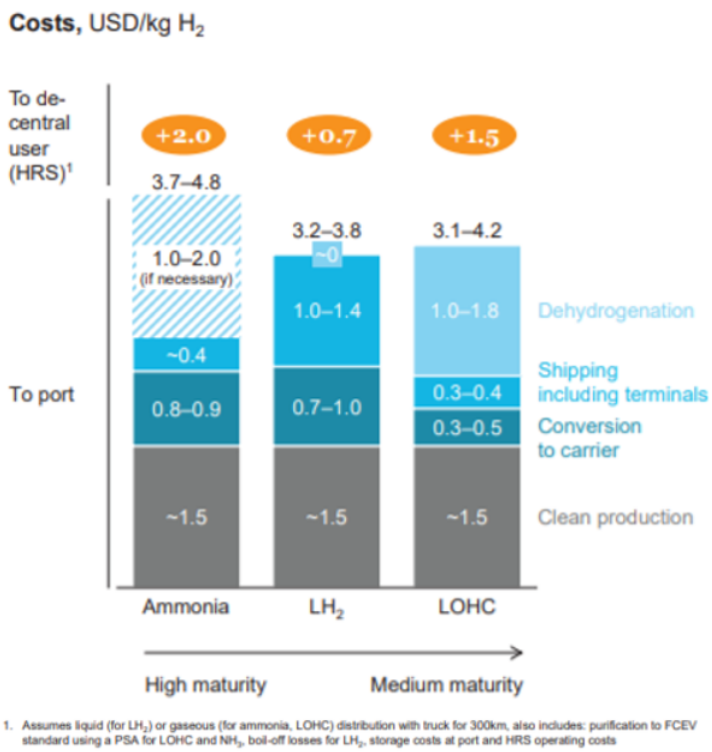


Figure 5: Cost of production and shipping from Saudi Arabia to the Port of Rotterdam (8,700 km) and further inland to Hydrogen Refuelling Stations (HRS) (HydrogenCouncil, 2020)

3.3. Hydrogen storage cost

Although there are many technologies to store hydrogen (Energy.gov), for large scale hydrogen storage compressed hydrogen storage in salt caverns is the most economic and mature technology today.

Salt caverns can be used to store hydrogen in the same way as that they can store natural gas. In the UK, a salt cavern has been in use for hydrogen storage already for many decades. Also in the US, salt caverns have been used to store hydrogen for many years.

In a typical salt cavern, hydrogen can be stored at a pressure up to 200 bar. The storage capacity of a salt cavern is up to 6,000 ton hydrogen (236.6 GWh HHV) (Pluijm, 2018). The total installation costs, including piping, compressors, and gas treatment, are about € 100 million (Michalski, et al., 2017), which is less than 0.5 €/kWh Capex cost for hydrogen storage.

The need for cheap hydrogen storage will grow exponentially over time. Salt caverns can provide this cheap hydrogen storage solution. Europe has still many empty salt caverns available for large scale hydrogen storage, but dedicated salt caverns for hydrogen storage capacity can be developed in the different salt formations in Europe. Potentially, hydrogen can be stored in empty gas fields that meet specific requirements to store hydrogen. However, this needs more research.

In a study by Jülich research centre (Caglayan, et al., 2020), the potential for hydrogen storage capacity in salt caverns has been investigated. There is a huge potential for hydrogen storage in salt caverns all over Europe. Total onshore salt cavern storage capacity is 23,200 TWh of which 7,300 TWh could be developed taking into account a maximum distance to the shore of 50 km. This maximum limit is set for the brine disposal. The offshore storage capacity is even larger than the onshore capacity, 61,800 TWh. It should be noted that the salt cavern storage capacity potentials are even larger than total final

energy consumption in Europe. Although not studied so far, a substantial potential for hydrogen storage in salt caverns is available at many other places in the world too.

4. Space and time dimensions in a renewable energy system

4.1. Good renewable energy resources at remote locations

Renewable energy resources, especially solar and wind, are unevenly distributed around the world. The good solar resources can be found in desert areas mostly around the tropics. The Sahara Desert, Australia, Namibia, Saudi Arabia, and Chile have the highest global irradiation, while countries such as India, the South of the USA, Mexico, Brazil, China, Iran and others also have good solar resources, see figure 6.

Good wind resources can be found in coastal areas (sea winds), but also in some desert areas, around the tropics (trade winds) and flat terrain areas such as in Patagonia, Kazakhstan, Mid-West USA, Mongolia, New Zealand, etc., see figure 7. However, at sea and ocean, the wind speeds are even higher than on land.

The good solar and wind resource areas are normally far from population locations and therefore energy demand. Besides, at these good resource areas the availability of space is abundant and population density low. Less than 10% of the Sahara Desert with solar panels, can produce all the energy for the world. Or at 1.5% of the Pacific Ocean placing large floating wind turbines could also produce all the world's energy (van Wijk, van der Roest, & Boere, 2017).

These good renewable energy resource areas are most of the time much larger in size then the population centres and have a low population density. As an example, the Sahara Desert, 9.2 million km^2, is two times as large as all the countries of the European Union plus the UK, almost 3 times as large as India and over 24 times as large as Japan. Moreover, it has a population density below 1 person per km^2, while the EU has a population density of 117 persons per km^2, India 382 persons per km^2 and Japan 347 persons per km^2.

4.2. Hydrogen as commodity to transport cheap solar and wind around the world

Although many regions in the world can produce renewable and/or low/no carbon hydrogen at low cost, it is obvious that certain regions will become net exporters and other regions will become net importers of renewable energy by hydrogen or hydrogen derivatives like ammonia. Even within regions, there will be hydrogen trade, import and export.

Japan, South Korea, parts of China, parts of USA, the European Union but also India will become net importer of low-cost hydrogen, see figure 8, not only because of their modest renewable energy resources, but also due to their restricted area size and high population density.

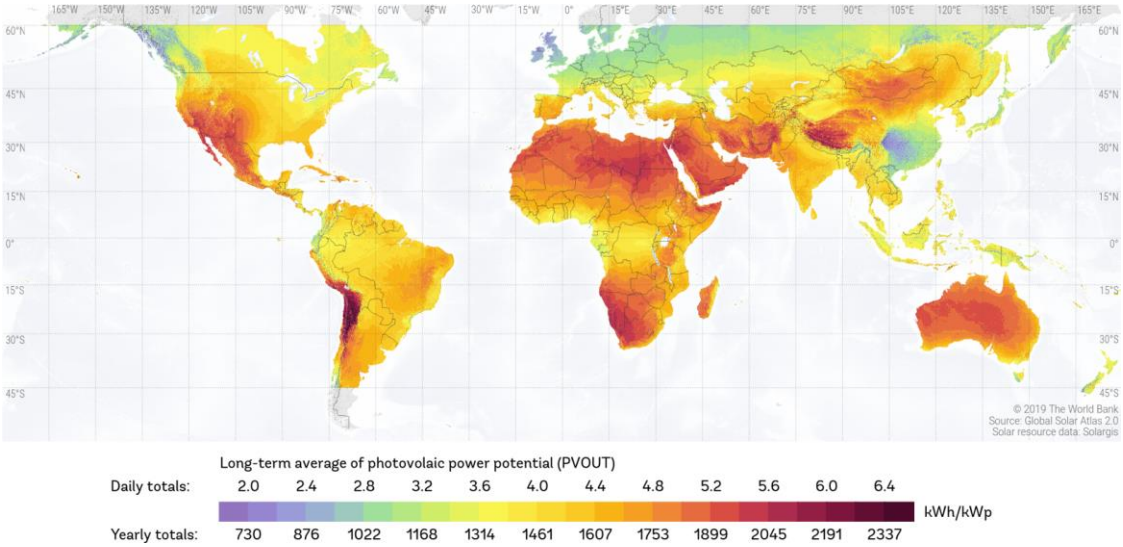


Figure 6: Solar Resources Map, Photovoltaic Power Potential (World Bank, Esmap, SolarGIS) (WorldBankSolar)

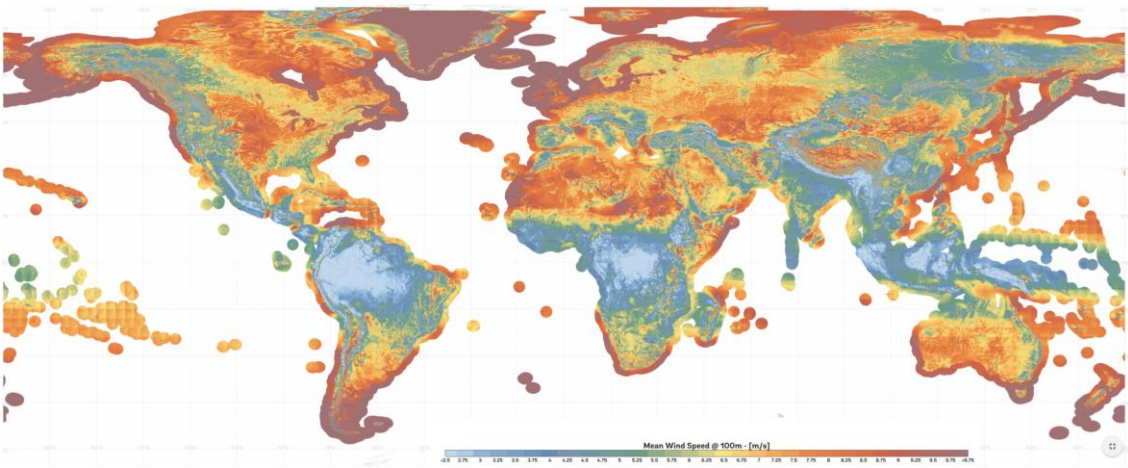


Figure 7: Wind Speed Map at 100 meters (World bank, Esmap, DTU wind energy, Vortex) (WorldBankWind)

Multi-GW production of solar and wind electricity at these good resource locations, conversion to hydrogen and transporting to the demand areas can deliver large quantities of cheap renewable electricity, transported in the form of hydrogen, all around the world. The imported hydrogen will eventually compete in price with locally and regionally produced hydrogen and even with locally and regionally produced electricity. Therefore, hydrogen and derivatives will become the energy commodity that can be internationally transported and traded (HydrogenCouncil & McKinsey, 2021).

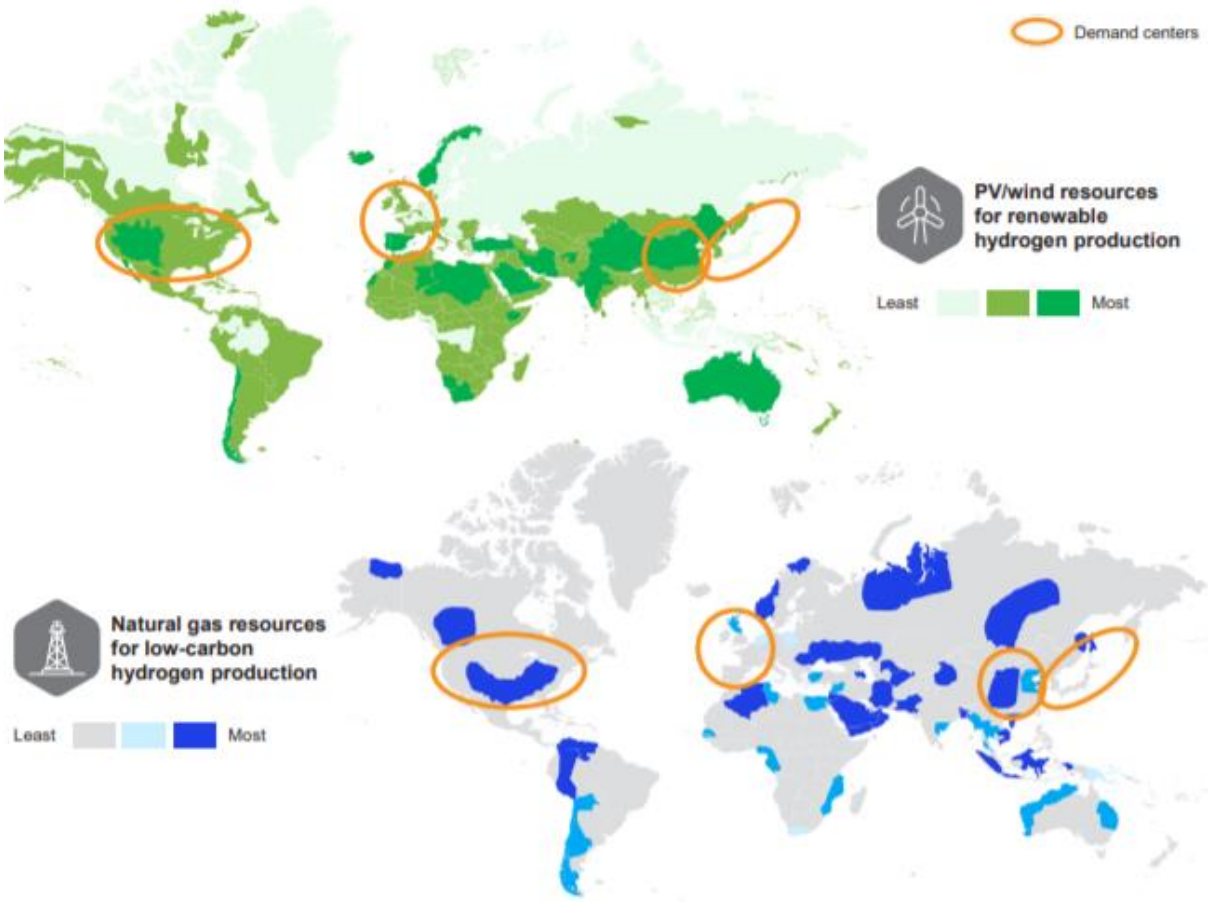


Figure 8: Global hydrogen resources and demand centres (HydrogenCouncil & McKinsey, 2021)

4.3. Space requirement for large scale renewable hydrogen production

In order to fully utilize the advantage of lower transport costs, an order of magnitude more hydrogen needs to be produced then electricity. A 1 or 2 GW wind or solar farm is for electricity production a sufficient size, because a HVDC cable has a capacity of 1 to 2 GW. However, for hydrogen production, a wind or solar farm needs to be sized, based on a hydrogen transport pipeline capacity, between 10-20 GW. If a transport pipeline has a capacity of 10 GW and the capacity factor of such a pipeline is about 4,000 full load hours, a volume of 40 TWh a year will be transported. This is roughly equivalent to 1 million tonnes of hydrogen. Production of 1 million tonnes hydrogen needs space: for the electricity production by solar or wind, for the electrolysers, compressors, cabling and pipelines, access roads, etc. Table 2 gives an overview of the required area that is needed to produce about 1 million tonnes of hydrogen (van Wijk, 2021).

As can be seen from table 2, for solar an area of about 500 km^2 is needed, more or less fully occupied with installations and equipment. Especially solar PV or CSP electricity production requires by far most of the space. An alkaline electrolyser has on average a two times larger footprint then a PEM electrolyser, however the space requirements for an alkaline electrolyser, 10 ha/GW (IEA, 2019) is modest compared to the space requirements for solar/wind electricity production.

For onshore and offshore wind, the physical space that a wind turbine needs is not much. In a wind farm, however, the turbines need to be spaced well apart from each other, due to wake effects and turbulence caused by wind turbines. A rule of thumb is a spacing of 7 times the rotor diameter

between two wind turbines (Borrmann, Rehfeldt, & Wallasch, 2018). Therefore, the total area needed to realize a wind farm, is much larger than the physical area needed. So, it is possible to use the land or sea for agricultural purposes or even to place large solar PV farms in between the wind turbines.

	Capacity Factor (Full load hours)	Installed capacity (GW)	Hydrogen production* (million ton)	Specific space requirement (km^2 / GW)	Space requirement (km^2)
Solar PV	1,800	30	1.10	16.5	500
Solar PV	2,100	25	1.07	16.5	420
Solar CSP	4,000	12.5	1.02	30	375
Wind onshore	4,000	12.5	1.02	3 (physical space) 170 (wind farm space)	38 2,125
Wind offshore	6,000	9	1.10	2 (physical space) 125 (wind farm space)	18 1,125

*Electrolyser system efficiency 80% HHV

Table 2: Space requirements for multi-GW solar and wind hydrogen production plants (van Wijk, 2021)

The estimated space requirements do not necessarily mean it has to be a contiguous area of 500-2,000 square kilometres. It could be smaller areas, not too far from each other, producing and transporting hydrogen through a smaller pipeline feeding into a large hydrogen transport pipeline.

4.4. Multi-GW low-cost green hydrogen potential in Europe and North Africa

Low-cost green hydrogen can be produced in areas with good solar and/or wind resources. However, the potential for large scale renewable electricity and hydrogen production will be limited by the availability of space. For Europe and North Africa, the solar and wind resource and area characteristics are shown in table 3.

The table shows that the Sahara Desert is more than two times larger than all countries of the European Union, that the population density differs a factor 117, while the solar and wind resource characteristics are better.

	Sahara Desert	European Union	Mediterranean Sea
Area Size (km^2)	9,200,000	4,272,000	2,500,000
Population density (person/km^2)	Less than 1	117	0
Solar resource	Excellent	Good in South Europe	Good to Very Good
Wind resource	Very good to excellent at several areas	Good in coastal areas and several other places	Good to excellent in the Eastern part

Table 3: Area size, population density and solar and wind resource characteristics for the Sahara Desert, European Union and Mediterranean Sea

A study using a GIS (Geographic Information System) modelling tool and data, has mapped for Europe and North Africa the levelized cost of hydrogen production as a function of the solar and wind resources, see figure 8 and 9 (Groenewegen, 2021). The lowest hydrogen production cost for both solar and wind on land can be found in the Sahara Desert. Although in the South of Europe reasonable low-cost hydrogen can be produced from solar. In the North of Europe and several other coastal locations in Europe also reasonable low-cost hydrogen from wind can be produced. Offshore wind hydrogen production has not been included, however at sea there is a potential for reasonable low-cost large scale hydrogen production as well.

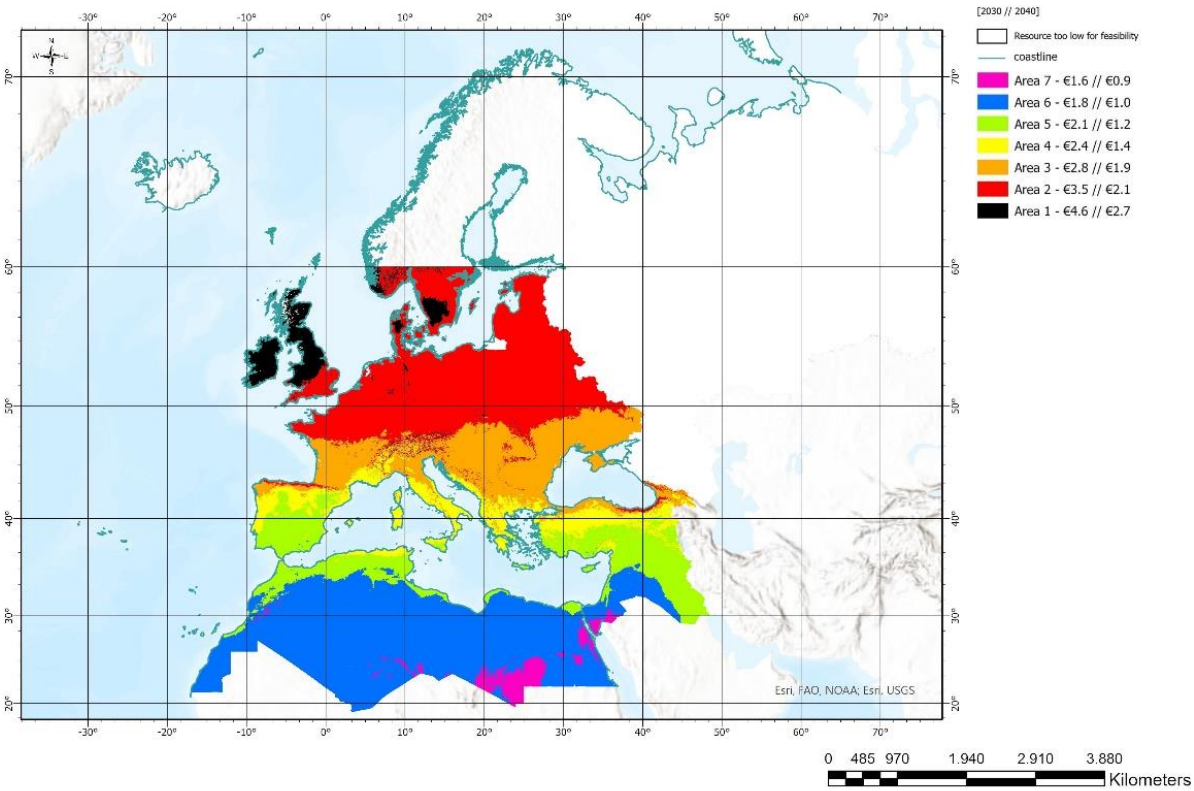


Figure 8: Levelized cost of hydrogen from solar electricity as a function of the solar resource for the years 2030/2040 (Groenewegen, 2021)

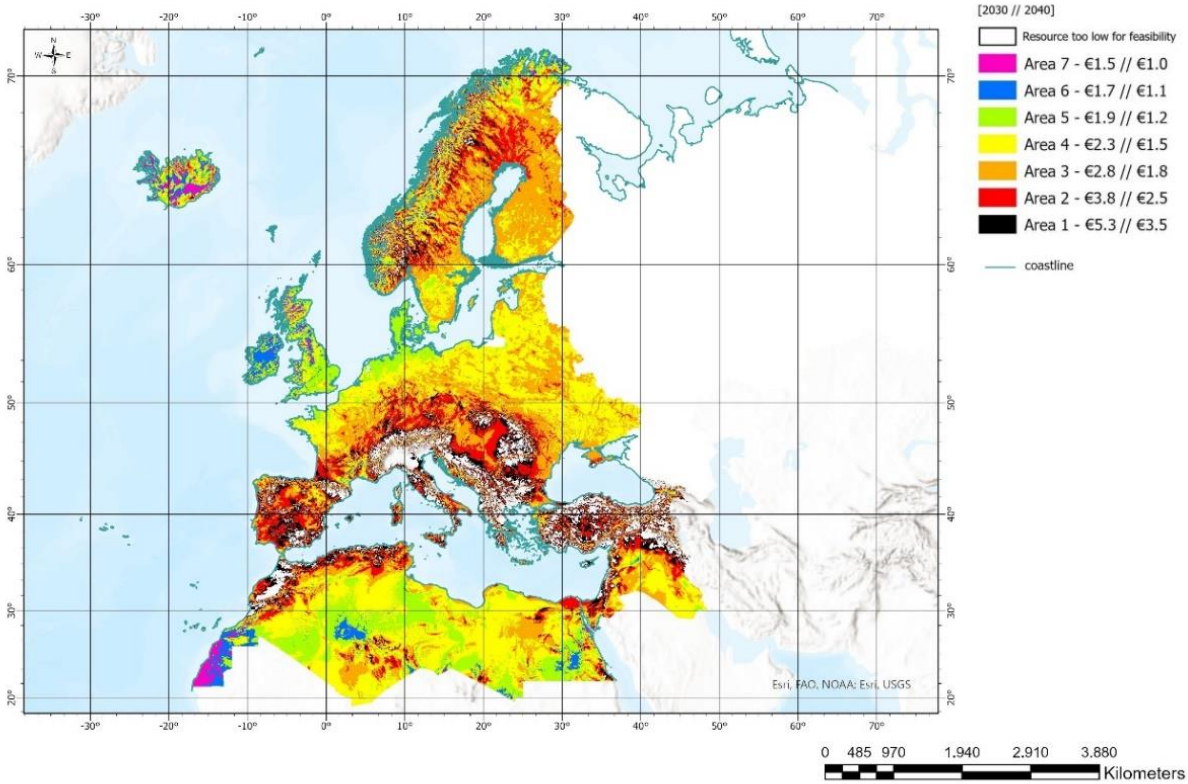


Figure 9: Levelized cost of hydrogen from wind electricity as a function of the wind resource for the years 2030//2040 (Groenewegen, 2021)

Even if the resource is good, multi-GW low-cost hydrogen production requires space which must be available. To produce between 0.5 to 2 million ton hydrogen requires about 500 km^2 for solar and about 1,000 km^2 for wind. For solar the land area is almost fully occupied with solar modules, while for wind only a limited amount of space is in use by the wind turbines. The GIS modelling tool has looked to these area sizes for solar and wind, whereby the following land areas were excluded:

- areas with more than 100 people/km^2,
- mountainous areas and areas of natural beauty,
- build areas, cities, industrial sites, and airport fields with a 10 km exclusion zone.

Figure 10 and 11 have mapped the LCoH as a function of the solar or wind resource whereby the above-mentioned areas are excluded. These maps show clearly that the available space for low-cost hydrogen production in the EU, especially in North-West and Mid Europe is restricted. However, in North Africa, the resources for both solar and wind are excellent and abundant space is available.

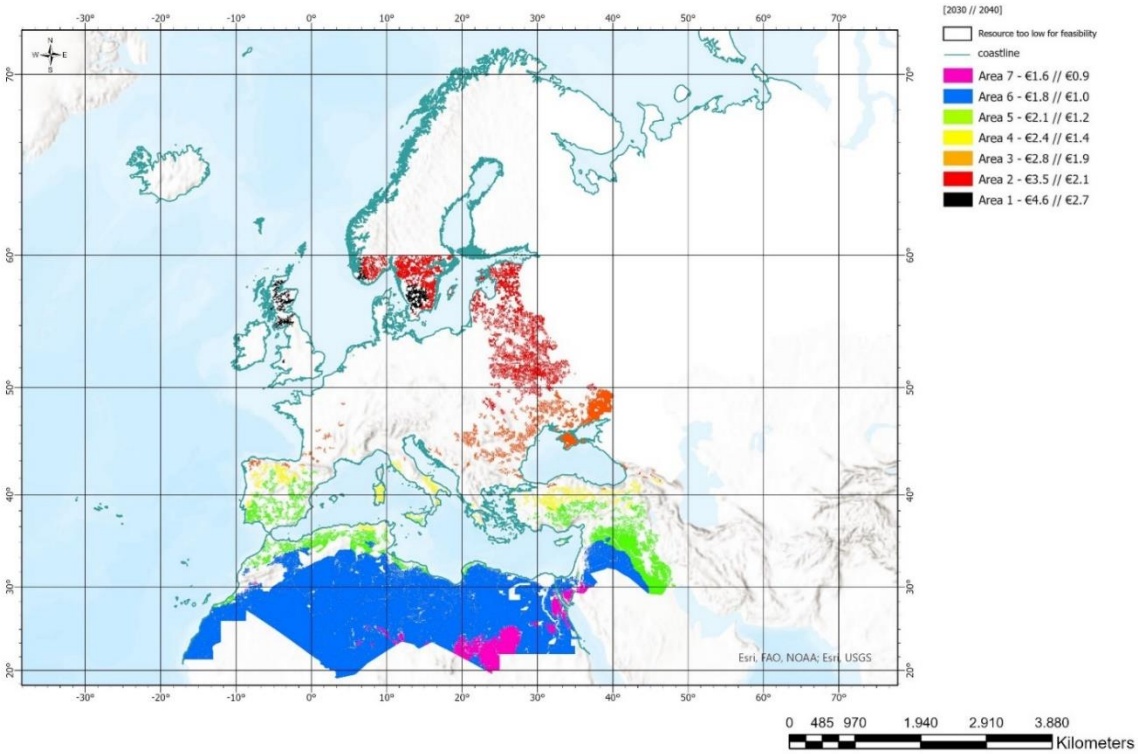


Figure 10: Levelized cost of hydrogen from solar electricity as a function of the solar resource with area restrictions for the years 2030//2040 (Groenewegen, 2021)

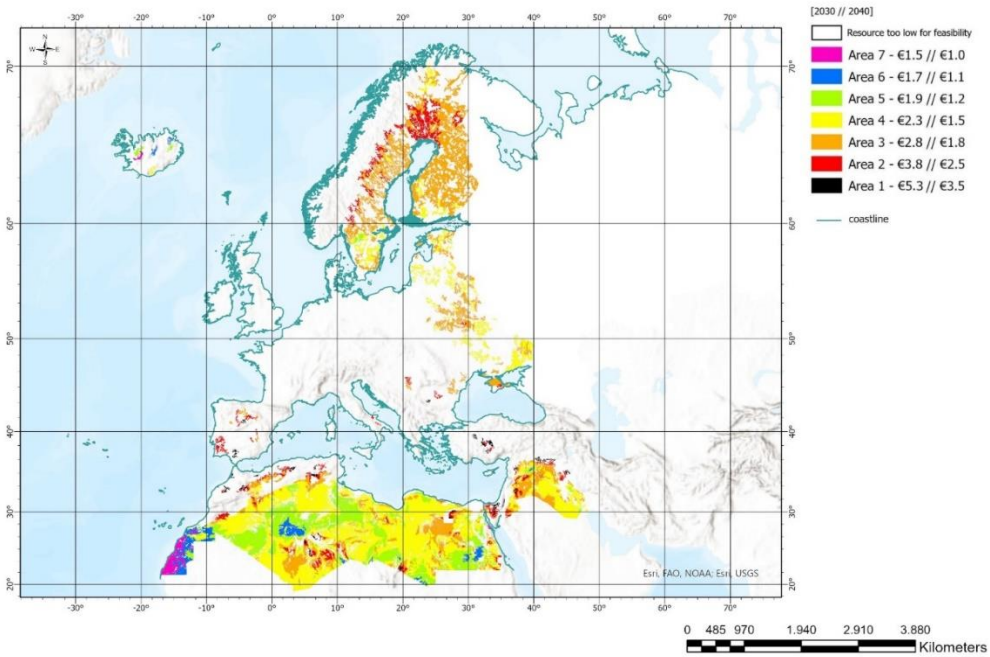


Figure 11: Levelized cost of hydrogen from wind electricity as a function of the wind resource with area restrictions for the years 2030//2040 (Groenewegen, 2021)

The potential for low-cost hydrogen production (LCoH below or equal to €1.5/kg) in North Africa, South Europe, and the EU for the year 2040, is given in table 4. The EU has a potential to produce low-cost hydrogen on land, especially from solar. The potential for hydrogen below €1.5/kg (in 2040) is about twice the total EU27 Primary Energy Consumption. In North-West and Mid European countries, the potential for large scale low-cost renewable hydrogen is practically zero, due to resource and available land area restrictions, see figures 11 and 12. Therefore, these countries will become net importers for low cost hydrogen. It has to be noted that offshore wind hydrogen production potential is not taken into account.

North Africa has a huge potential for hydrogen production. Almost 1.1 million TWh hydrogen can be produced which is even more than 6 times world primary energy consumption.

	North Africa (Morocco, Algeria, Tunisia, Libya, Egypt)	South Europe (Portugal, Spain, France, Italy, Malta, Slovenia, Croatia, Bosnia H., N. Macedonia, Albania, Montenegro, Serbia, Greece, Cyprus)	European Union 27 Countries
Hydrogen potential			
Solar			
Mton H_2	24,400	815	815
TWh$_{(HHV)}$ H_2	961,300	32,100	32,100
Wind			
Mton H_2	2,700	10	65
TWh$_{(HHV)}$ H_2	106,400	400	2,600
Total			
Mton H_2	27,100	825	880
TWh$_{(HHV)}$ H_2	1,067,700	32,500	34,700
Primary Energy Consumption TWh	2019 World 159,000		2019 EU 17,000

Table 4: Hydrogen production potential with LCoH (Levelized Cost of Hydrogen) below €1.5/kg in 2040 in North Africa and the EU

4.5. Baseload renewable hydrogen supply cost Morocco to Germany by pipeline

The Levelized Cost of Hydrogen (LCoH) for base load hydrogen from Morocco supplied to Germany over a distance of about 3,000 km has been calculated as an example. Figure 12 shows wind speed and irradiation maps for Morocco. It can be noticed that Morocco has good solar and wind resource areas. Figure 12 shows also a map of the salt formations in Morocco. Most of these salt formations are at sea in front of the Moroccan coastline (Tari & Jabour, 2013). However, one part of the salt formation is onshore, the Essaouira basin above Agadir and this area has also good solar and wind resources.

It seems possible to develop salt caverns for hydrogen storage in this area, although further research has to be conducted to be sure that it is possible and feasible. It seems also possible to produce solar electricity in this area at a cost below 0.01 €/kWh and wind electricity below 0.02 €/kWh in 2030.

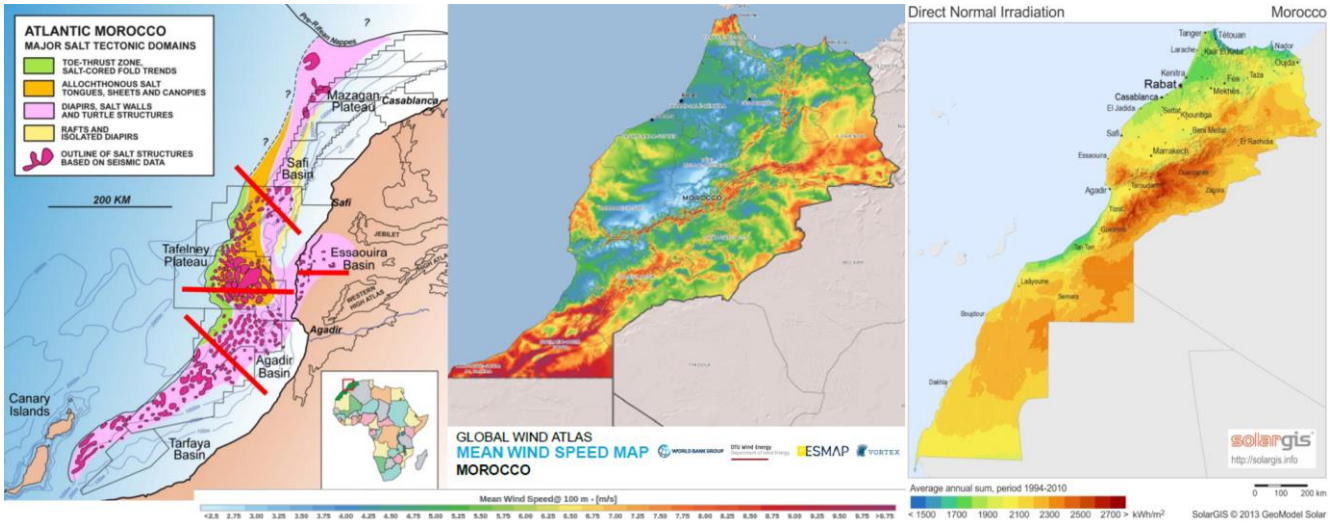


Figure 6: Salt formations, mean wind speed and solar irradiation maps for Morocco (Tari & Jabour, 2013) (WorldBankWind) (WorldBankSolar)

The solar hydrogen cost, delivered as base load hydrogen in Germany, transported by pipeline from Morocco, has been calculated. Of course, solar hydrogen production is not base load hydrogen production, it shows a daily and seasonal production cycle. By storing part of the hydrogen during day peak hours production, and releasing it during nights hours, a daily base load hydrogen supply into the pipeline can be realized. By storing part of the production in summer months to release it in winter months a base load supply into the pipeline over the year can be realized. These storage cost has been analysed for a Portuguese case with solar hydrogen production and storage in newly realised salt caverns (Quintela de Saldanha, 2021). These storage cost add about 0.1-0.2 €/kg to the hydrogen cost. Base load hydrogen transport by a 20 GW capacity hydrogen pipeline, requires a yearly energy volume of 20 GW*8,000 hours= 160 TWh hydrogen, which equals over 4 million ton hydrogen. To produce this amount of hydrogen by solar electricity in Morocco, roughly 100 GW solar PV is needed, requiring 2,000 km^2 space. With solar PV electricity cost between 0.01-0.02 €/kWh and electrolyser Capex cost of 200 €/kW, the hydrogen production cost is between 1.0 and 1.5 €/kg. Transport cost over 3,000 km to Germany with cost of €0.1/kgH_2/1000km are 0.3 €/kg. Total cost to deliver base load hydrogen from Morocco to Germany are then between 1.4 and 2.0 €/kg H_2 or 0.035-0.050 €/kWh (HHV) H_2, see table 5.

Base load solar H_2 from Morocco to Germany		LCoH, Levelized Cost of Hydrogen
	Assumptions	
Solar-Hydrogen production	Solar electricity cost = 0.01-0.02 €/kWh Full load hours = 2,000 hours/yr Electrolyser efficiency = 50 kWh/kg H_2 100 GW solar = 4 million ton H_2 Required surface = 2,000 km^2	1.0-1.5
Salt cavern storage	Flexible production to base load; daily cycles	0.1-0.2
Pipeline Transport	Pipeline capacity = 20 GW Full load hours = 8,000 hours/yr Pipeline length = 3,000 km	0.3
TOTAL		**1.4-2.0 €/kg H_2** **=0.035-0.050 €/kWh(HHV) H_2**

Table 5: Levelized cost of hydrogen (LCoH) for base-load solar hydrogen supply from Morocco delivered in Germany

5. Hydrogen system design

5.1. Present gas, electricity, and hydrogen system characteristics

The gas system is an order of magnitude larger than the electricity system both in volume as well as in capacity. The hydrogen system is at present not an energy system because there is no public and large-scale infrastructure and can be characterised as part of the natural gas system. Gas is thereby providing the necessary flexibility for the electricity system as well as for the hydrogen system. The following scale observations can be made:

- Gas production at gas fields have a larger size in production volume and are located further from demand sites then power plants. In general, the dimensions in production volume and distance are about a factor 10 larger in the gas system compared to the electricity system.
- Gas can be transported over long distances and with large volumes by pipeline (continental to intercontinental) or ship (worldwide). Electricity can be transported via cables (regional to continental). In general, the dimensions in transport pipeline/cable length and capacity are a factor 10 larger in the gas system compared to the electricity system.
- Gas supply and demand balancing is via large scale gas storage. Electricity production and demand balancing needs to be done at every moment by ramping up and down power plants. There is some storage in the electricity system via pumped hydro power, but in fact the gas system delivers the flexibility in the electricity system.

- Gas is supplied by pipeline to hydrogen production plants, located at or near the hydrogen demand. There is only a limited privately owned hydrogen pipeline infrastructure. The gas systems provide the necessary flexibility for hydrogen production.

In table 6 system characteristics for present gas, electricity and hydrogen systems are presented.

	Gas system	**Electricity system**	**Present Hydrogen system**
Production volume per location	10-1,000 TWh/yr Gas field	1-30 TWh/yr Power Plant	0.1-4 TWh/yr SMR plant
Distance between production location and demand centres	Up to 4,000 km Pipeline Worldwide Shipment	Up to 1,000 km Cable	'Captive' production only for demand on location
Capacity Transport Pipeline/Cable	10-35 GW Pipeline	1 (HVAC) - 4 GW Cable (HVDC)	Some small pipeline infrastructure on and between industrial sites
Infrastructure ownership	Public or Private (e.g., at North Sea, intercontinental)	Public or Publicly regulated Private	Private
Storage Capacity	200-500 GWh Salt cavern Gas Empty Gas field storage capacity factor 10 larger than salt caverns	5-25 GWh Pumped hydro-power storage Largest battery storage systems announced < 1 GWh	100-250 GWh Salt cavern H_2 A couple of salt caverns are in use for H_2 storage

Table 6: System characteristics for present gas, electricity and hydrogen systems (van Wijk, 2021)

5.2. Renewable and no-carbon fossil hydrogen production characteristics

Hydrogen can contribute to a fast, cheap, and reliable transition to a sustainable energy system, whereby hydrogen will fully replace natural gas and other fossil fuels. Hydrogen production will be at or near the resources, both large and small scale, and will connect to a hydrogen infrastructure. So, the system characteristics for hydrogen production will become:

- Large scale hydrogen production at the good solar and wind resource areas. At least with a production volume of 1 million ton (39.4 TWh $_{HHV}$) hydrogen. Such an amount of hydrogen can be produced from 25 GW solar PV or from 10 GW offshore wind at the good resource locations.
- Large scale no-carbon hydrogen production from fossil resources at the gas (or coal) field locations for an intermediate time period. Typical production sizes will be comparable with production volumes from the gas or coal field. Production volume at gas fields could therefore be as large as 10 million ton per year (394 TWh $_{HHV}$).
- Hydrogen and carbon dioxide production from (biogenic) waste. The (biogenic) waste will be converted to H_2 and CO_2. H_2 will be fed into the hydrogen grid and CO_2 will be transported by pipeline or truck to the chemical industry or greenhouses as a feedstock.
- Hydrogen production from local renewable electricity production, to alleviate electricity grid capacity constraints.

5.2.1. Large scale base-load renewable hydrogen production at resource not at demand

Large scale multi-GW renewable hydrogen production will take place at the renewable resource location and not at the hydrogen demand locations. Electrolysers will be integrated with the renewable electricity production technology, e.g., solar cells and wind turbines and are not connected to an electricity grid. Hydrogen production from renewables is variable, but by system design plus

dimensioning and integrating (underground) hydrogen storage, as much as possible base load hydrogen is supplied to hydrogen transport pipeline infrastructure. There are several reasons to convert renewable electricity at the good resource locations into hydrogen.

- Integrating solar cells/modules with electrolyser stacks or integrating wind turbines with electrolyser stacks will result in lower overall investment cost than separated solar farms or wind farms and electrolyser plants and therefore lower hydrogen production cost, see chapter 3.1.3.
- Hydrogen transport by pipeline is more cost-effective (up to a factor of 10) than electricity transport by cable, see chapter 3.2.1.
- Hydrogen transport pipeline capacities (10-20 GW) are in general a factor of 10 larger than electricity transport cable capacities and hydrogen transport by pipeline over distances of at least 5,000 km is possible and feasible, see chapter 3.2.1.
- Hydrogen can not only be transported by pipeline but also by ship, see chapter 3.2.2.
- Large scale hydrogen storage facilities, mainly underground (salt caverns or possibly empty gas fields), need to be integrated in a hydrogen infrastructure system to be able to deliver renewable hydrogen at the time of demand. In many places on earth, at gas resource locations but also at good solar and wind resource locations, salt formations are present to realize large scale and cheap hydrogen storage, see chapter 3.3.
- Industrial energy demand for feedstock and high temperature in steel production, refineries, and synthetic fuel production, fertilizer, methanol, and other basic chemical products are baseload energy demand. Therefore, baseload energy, has to be supplied to these industries, but also for other industries: pulp and paper, food processing, glass and ceramics, where the energy demand is baseload sometimes week/weekend or day/night pattern. Besides, energy demand for mobility is essentially also a baseload energy demand. Base load hydrogen supply is easier and more cost efficient to realize at large volumes than base load renewable electricity, see chapter 3.3.
- Only for space heating and cooling and for lighting a seasonal, weekly, and daily pattern in energy demand exist, depending on local climatological conditions. Hydrogen, like natural gas, can be stored over seasons and can hence serve as a dispatchable source of bulk energy, a distinctive advantage over renewable electricity.
- Large volumes of renewable, solar and wind, hydrogen production requires large amounts of space, see chapter 4.3. Governments needs to develop especially spatial planning and infrastructure policies and needs to designate areas for large scale renewable hydrogen production in order to realize sufficient volumes of renewable energy to decarbonize the total energy system. But if space and/or good renewable energy resources are not available, renewable energy can be imported via hydrogen.

5.2.2. No-carbon fossil hydrogen production at the resource

No carbon fossil hydrogen production, from natural gas, is technologically possible via several technologies. Natural gas can be converted in hydrogen and solid carbon by methane pyrolysis, or in hydrogen and CO_2, with 100% CO_2 capture by autothermal reforming (ATR), see chapter 2.1. (The process to convert a fossil fuel into hydrogen and CO_2, whereby the CO_2 is captured and stored, is also called pre-combustion CCS.) There are several reasons to convert natural gas at the fossil resource site into hydrogen:

- If CO_2 is produced, the CO_2 can be stored into the underground, e.g., the gas field, without the need for a large CO_2 pipeline or other transport system to the underground storage.
- The gas pipeline infrastructure that transports the natural gas to the demand, can be fully converted to hydrogen. Large volumes of hydrogen can be transported to the demand, which

makes a fast and complete transformation from natural gas and other fossil energy use to hydrogen possible.

- Such a complete conversion of pipeline and storage infrastructure to hydrogen makes it possible to feed in renewable variable hydrogen production much easier at lower transport and storage cost.
- CO_2 emissions at the demand by using hydrogen are zero, in industry, electricity balancing, mobility and for high and low temperature heating. No post-combustion carbon capture, whereby the CO_2 has to be separated from flue gasses, transport and storage is necessary anymore. In general, post-combustion CCS is more expensive than pre-combustion CCS.
- Converting natural gas at the gas resource field into hydrogen, makes it possible to control methane leakage from the gas field much better, with lower methane leakages.
- Converting the natural gas pipeline and storage infrastructure fully to hydrogen will result in zero methane leakage for transport and storage.
- New gas exploration, whereby already a concession is granted, with conversion to hydrogen at the resource makes exploration of this natural gas still possible. Governments do not have to buy out at high cost, these exploration concession rights, to reduce greenhouse gas emissions. Governments only have to impose strict no-carbon emission standards for gas input in the infrastructure.
- Conversion to hydrogen by new gas exploration **avoids a 'natural gas/methane' lock in**, because when this 'new' natural gas is feed into the energy system it will be there for the lifetime of the gas field, 30-40 years.

5.2.3. Hydrogen and carbon(dioxide) production from (biogenic) waste streams

Hydrogen and carbon (dioxide) can be produced from biogenic waste streams, but also from chemical waste streams such as plastics. At present large volumes of solid waste streams, wood residues, plastics, etc. are burned to produce heat and electricity and emits flue gases with CO_2 to the air. Wet biogenic waste streams, such as sludge or manure, are digested to produce a biogas. This biogas can be burned to produce heat and electricity or can be upgraded to natural gas quality to feed into the gas grid and, in the end, it will be also burned. In all cases CO_2 is emitted into the air. In future zero-emission energy systems, however, it is more efficient, economic, and less polluting to convert these solid and wet (biogenic) waste streams into H_2 and CO_2, because of the following reasons:

- Both hydrogen and carbon dioxide are useful products in a fully decarbonized energy and feedstock system. Hydrogen can be used as feedstock and as an energy carrier. However, CO_2 is also a feedstock for chemicals, synthetic fuels and in greenhouses for increased crop growth. Both hydrogen and carbon dioxide can avoid fossil CO_2 emissions to the air. Therefore, converting a biogenic waste stream in H_2 and CO_2, even negative fossil fuel CO_2 emissions can be realized.

- Converting biogas to hydrogen and CO_2 **avoids a 'natural gas infrastructure' lock in**. There is no necessity for a natural gas infrastructure anymore. Hydrogen can be fed into the hydrogen infrastructure. The carbon dioxide can be made liquid and transported by truck, or at large conversion plant even a CO_2 pipeline infrastructure can be realized for transport to chemical sites and greenhouses.

- Converting biogas immediately into hydrogen and CO_2, makes it possible to control methane leakage from biogas production much better, with lower methane leakages.

- Converting fully the natural gas/biogas pipeline and storage infrastructure will result in zero methane leakage for transport and storage.

- For new (biogenic) waste streams energy production plants governments needs to impose strict no-greenhouse gas (CO_2 and methane) emission standards for gas input in the infrastructure and needs to impose regulation for the use of CO_2 as feedstock.

5.2.4. Hydrogen production to alleviate electricity grid capacity constraints

Integrating increasing volumes of variable solar and wind electricity into the electricity system becomes challenging due to grid capacity constraints and balancing electricity supply and demand. At high solar and wind production the grid capacity and/or the demand for electricity could be the limitation for uptake in the electricity grid, resulting nowadays in curtailing electricity. When solar and wind production is low when demand is high, today still fossil fuelled power plants serve to balance supply with demand. However, in the future, balancing electricity supply and demand needs to be done without greenhouse gas emissions too. Especially both electricity and hydrogen production from solar and/or wind farms with a hybrid connection to the electricity grid and the hydrogen infrastructure can alleviate grid capacity constraints and contribute to balancing. Such an integrated and coupled electricity and hydrogen system is interesting because of the following reasons.

- When part of the capacity of a solar or wind farm is connected to the electricity grid and the other part to an electrolyser, more solar and wind production capacity can be integrated into the total energy system and thereby **alleviate the need for electricity grid capacity expansion.**
- When the electrolyser is also coupled to the electricity grid it is also possible to uptake excess produced electricity from renewables. And such a hybrid coupled electrolyser can deliver flexibility services to the grid.
- The electrolyser must be able to produce sufficient volumes of hydrogen at competitive cost to meet local hydrogen demand (e.g., fuelling stations, local industry, and heating). For this it is necessary to 'buy' renewable electricity from the grid.
- The locally produced hydrogen can be fed into a local hydrogen infrastructure that is connected to a hydrogen transport infrastructure. Surplus hydrogen can now be transported to large scale underground storage facilities for weekly to seasonal storage.
- The capacity of a hydrogen infrastructure (the re-used natural gas infrastructure) is in general larger than the capacity of the electricity infrastructure and can deliver the necessary volumes, capacities, and flexibility for the electricity and also for the total energy system. By using small scale fuel cell systems in buildings, neighbourhoods or in fuel cell cars, electricity can be produced locally to balance supply and demand and thereby also avoid or **alleviate electricity grid capacity expansion** because of increased electricity demand.

5.3. Future hydrogen system lay out

A future hydrogen system will therefore look a lot like the present natural gas system. The lay-out of such a future hydrogen system will consist of the following, see figure 7.

- Large scale renewable hydrogen production sites will be connected with gathering lines to underground storage facilities to balance production fluctuations and hydrogen processing plants to bring it on specification.
- In an intermediate period large scale no-carbon hydrogen production from fossil fuels at the resource sites with carbon capture and storage directly in the gas field can provide hydrogen volume in the system. Gathering lines will transport the hydrogen to hydrogen processing plants to bring it on specifications.
- Intercontinental and continental transport pipelines will transport the hydrogen to the demand centres. This transport will be mainly baseload hydrogen transport.
- At Ports Hydrogen can be imported via LH2, ammonia or LOHC by ship and temporarily stored in tanks and/or fed into a hydrogen infrastructure.

- Hydrogen is then transported to large volume, base load, customers (e. g., chemical industry, steel plants, synthetic fuel production plants) and to underground storage facilities to balance daily to seasonal demand fluctuations.
- Hydrogen is also transported to city gate stations, whereby pressure levels are reduced to medium pressure levels, connecting medium volume customers; industries (e.g., food processing, paper, special chemicals, data centres) large commercial sites (e.g., distribution centres, campus sites, offices, and stores) and hydrogen fuelling stations.
- At medium pressure, local and regional hydrogen production from (biogenic) waste streams brought on specification can be fed in the hydrogen grid.
- At medium pressure, also local and regional hydrogen production from renewable electricity, to alleviate electricity grid capacity constraints, can be fed into the hydrogen grid.
- Lastly, hydrogen is distributed at low pressure levels to residential customers (e.g., houses, small shops, offices, schools).

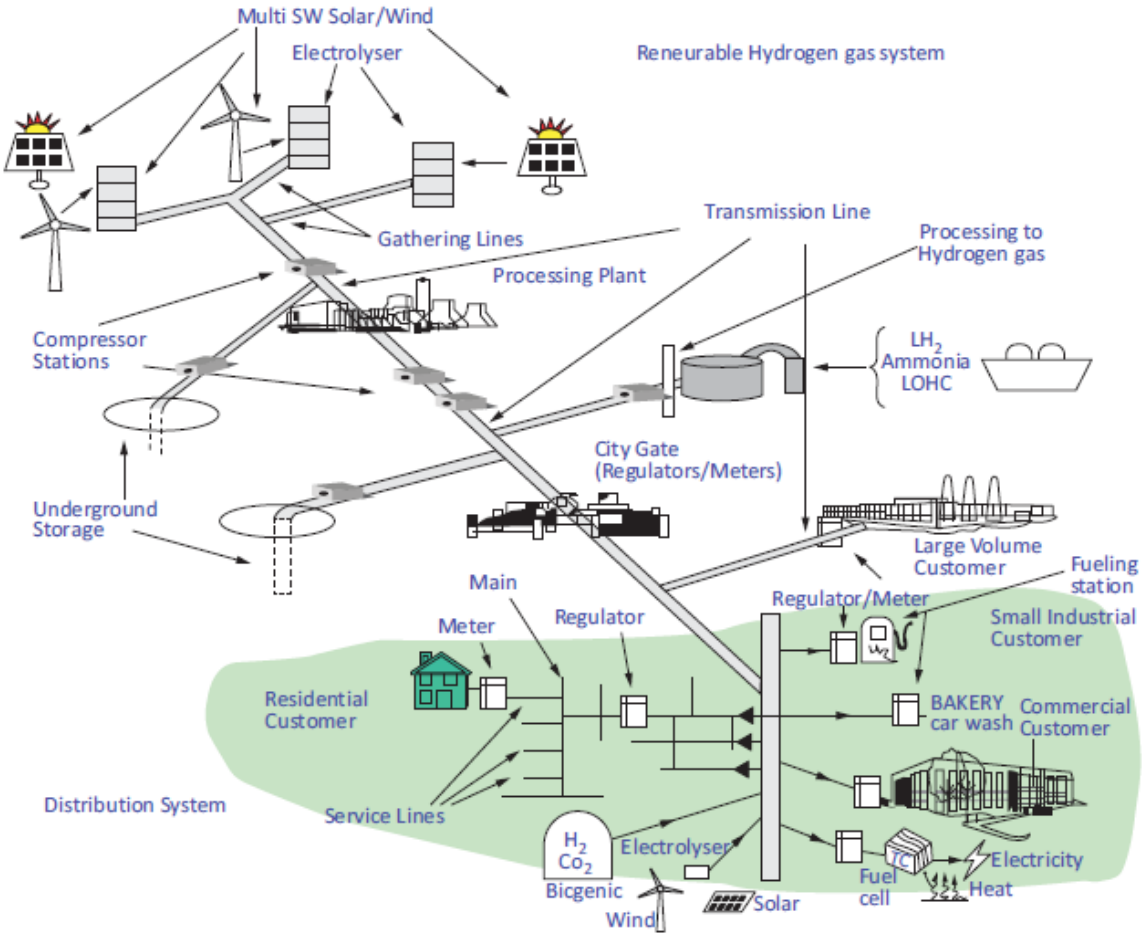


Figure 7: A schematic lay out of a future renewable hydrogen gas system (van Wijk, Hydrogen key to a carbon-free energy system, 2021)

6. Conclusions

6.1. Hydrogen is an energy carrier, like electricity

Hydrogen is a carbon-free energy carrier, which means that there are no CO_2 emissions to the air, when it is used. Hydrogen, like electricity, can be produced from fossil energy sources, oil, gas, and

coal, but also from biomass and (biogenic) waste streams as well as from water using electricity, heat, or sunlight as input energy.

Both hydrogen and electricity can be produced from both fossil and renewable energy resources without CO_2 emissions to the air and hydrogen and electricity can be converted into each other. Therefore, both will become the dominant carbon-free energy carriers in the future net-zero greenhouse gas emitting energy system.

6.2. Hydrogen as global energy commodity for transport and trade

At the good solar and wind resource locations around the world, at present GW scale solar electricity can be produced for 0.01 €/kWh and wind electricity for 0.02 €/kWh. In the future, these prices will decrease further. But in moderate solar and wind resource locations, the production costs are between 2 and 5 times higher.

Converting to hydrogen makes transport and storage of cheap renewable solar and wind energy possible and feasible. Large volumes of hydrogen transport by pipeline are about 10 times cheaper than electricity transport by cable, while hydrogen storage cost in the underground is at least 100 times cheaper than electricity storage cost by pumped hydro or by batteries.

It is feasible to transport hydrogen by pipeline at least up to distances of 5,000 km. At larger distances also transport by ship via ammonia, liquid hydrogen or bound to a liquid hydrogen carrier (LOHC) becomes feasible and makes hydrogen supply possible from all over the world. Hydrogen and its derivatives will therefore become the zero-carbon energy commodity that can be traded globally in a future net-zero greenhouse gas emitting energy system.

6.3. Hydrogen import and export regions

Excellent and good renewable, solar and wind, energy resources are unevenly distributed around the world. Good solar resources can be found in desert areas around the tropics. Good wind resources can be found at sea, in coastal areas (e.g., sea winds), but also in some dessert areas, around the tropics (trade winds) and flat terrain areas (e.g., Patagonia, Kazakhstan, ...). These good resource areas are normally far from population centres and energy demand. Besides, in many regions around the world, in places where the energy demand is located, it is not possible to produce enough renewable electricity, due to all kinds of constraints, such as available area size, population density and opposition or other area restrictions (e.g., nature reserves, airfields, etc.).

This makes large scale conversion to hydrogen for cost efficient transport and storage of cheap solar and wind energy a necessity. Regions such as Europe, Japan, parts of the USA, China, and India, will become net hydrogen importers, while other regions such as Australia, the Middle East, large parts of Africa and South America plus the oceans will become net hydrogen exporters.

6.4. Cost competition between import and regional produced renewable energy

A scaled-up hydrogen industry could deliver base-load hydrogen by pipeline for about 1-2 €/kg H_2 =0.025-0.050 €/kWh($_{HHV}$) H_2 at many parts in the world in 2050. Of course, hydrogen can be used to de-carbonise hard to abate sectors. However, imported hydrogen will also compete with local produced renewable energy, especially with renewable electricity and hydrogen from solar and wind. Energy use will become a trade-off and competition between local/regional produced electricity, regional produced hydrogen and imported hydrogen in all sectors and applications, e.g., for high-temperature heat in industry, for mobility, for heating/cooling buildings/houses and for electricity production/balancing.

6.5. Spatial planning for multi-GW renewable electricity and hydrogen production

Producing large amounts of renewable hydrogen requires space and time to realize multi-GW solar and wind hydrogen production plants. Hydrogen transport infrastructure and hydrogen demand also have to be developed at the same time, whereby hydrogen production and demand needs to be balanced in time.

It is certainly possible to realize a renewable energy system, with no greenhouse gas emissions to the air in 2050 and hydrogen will be a key energy carrier and commodity of such a system. However, the development of large-scale sites for renewable hydrogen production requires governments to designate areas for large scale renewable electricity and hydrogen production. The government will have to select such areas based on a number of criteria. Zoning plans will have to be drawn up for these areas, an environmental impact analysis will have to be carried out, infrastructure such as roads and communication will have to be constructed and infrastructure operators will have to construct the large-scale hydrogen transport and storage infrastructure and necessary electricity infrastructure.

6.6. Transition via no-carbon fossil hydrogen to renewable hydrogen

The transition from a fossil-based energy system that emits CO_2 to the atmosphere to a renewable energy system without CO_2 emissions, is a challenge. Realizing sufficient volumes of large-scale low cost solar and wind electricity and hydrogen production that can replace all fossil energy use worldwide, will take several decades. A transition path, that reduces CO_2 emissions quickly and cost-efficiently, is possible. Such a pathway can be speed up by large-scale hydrogen production from natural gas directly at the gas field, without any CO_2 emissions to the air. Via ATR technology with 100% carbon capture and storage immediately in the gas field and via methane pyrolysis whereby only solid carbon is formed without CO_2 emissions, no-carbon fossil hydrogen can be produced in large volumes. This will make it possible to convert the natural gas transport and storage infrastructure much faster and completely into a pure hydrogen infrastructure also avoiding methane emissions from the process and infrastructure. The CO_2 emissions will be reduced faster and in larger volumes too. And in such a hydrogen system, it will become easier and cost efficient to feed in renewable hydrogen. No-carbon fossil hydrogen production from natural gas at the gas field avoids therefore a 'natural gas' lock in.

6.7. Future hydrogen system characteristics

Future hydrogen systems will have similar characteristics as present-day natural gas systems. Large-scale multi-GW renewable hydrogen production plants, producing more than 1 million tonnes (=39.4 TWh $_{HHV}$) H_2/year at good resources sites needs to be developed. Hydrogen production cost will be below 1 €/kg H_2 around 2030 and will become competitive with present day gas prices around 2040. Hydrogen infrastructure can be realized by re-purposing gas infrastructure, pipelines, and salt cavern storage, without major adaptations.

As a transition, hydrogen produced from fossil fuels at the resource sites with carbon capture and storage directly in the field below or with only solid carbon as by-product, can bring no-carbon hydrogen volume in the system. Regionally and locally hydrogen and CO_2 can be produced from (biogenic) waste streams, whereby the produced CO_2 is circular or green and can be used as a circular or green feedstock. Locally produced hydrogen from solar and wind electricity will complement imports and will help to alleviate electricity grid capacity constraints. Hydrogen can deliver, in a similar way as natural gas does today, the necessary flexibility at daily, weekly, and seasonally time scales that a fully renewable electricity and energy system will require. Such an approach can establish a fast, cheap, reliable, secure, and inclusive transition to a sustainable energy system, whereby hydrogen will fully replace natural gas, coal, and oil.

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