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2x40 GW Green Hydrogen Initiative for a "European Green Deal"

Hydrogen Europe

African Hydrogen Partnership

Ukrainian Hydrogen Council

Cleanergy.Net EU-GCC

Dii Desert Energy
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EU-GCC Clean Energy Technology Network https://www.eugcc-cleanergy.net/

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Summary

Hydrogen can play a crucial role in achieving both a clean and prosperous economy.

Pivotal role of hydrogen in a sustainable energy system

Climate change is a serious problem, urging us to significantly reduce greenhouse gas emissions across all sectors. This implies radical changes towards a sustainable and circular economy that is at the same time constructive and competitive. Hydrogen can play a crucial role in achieving both a clean and prosperous economy.

Hydrogen and electricity are both carbon free energy carriers that can be produced from fossil energy resources as well as renewable energy resources. Both carriers will be necessary in a sustainable energy system and are very much complementary to each other.

Hydrogen allows for cost-efficient bulk transport of energy over long distances together with cost-effective storage of large energy volumes. Hydrogen can therefore decouple energy production and usage in location and time. Additionally, hydrogen can be used to decarbonise all energy use:

- in industry, both for feedstock and high temperature heat,
- in mobility, for road, rail, water and air transport,
- in buildings, for heating and cooling,
- in electricity, to balance electricity demand and supply

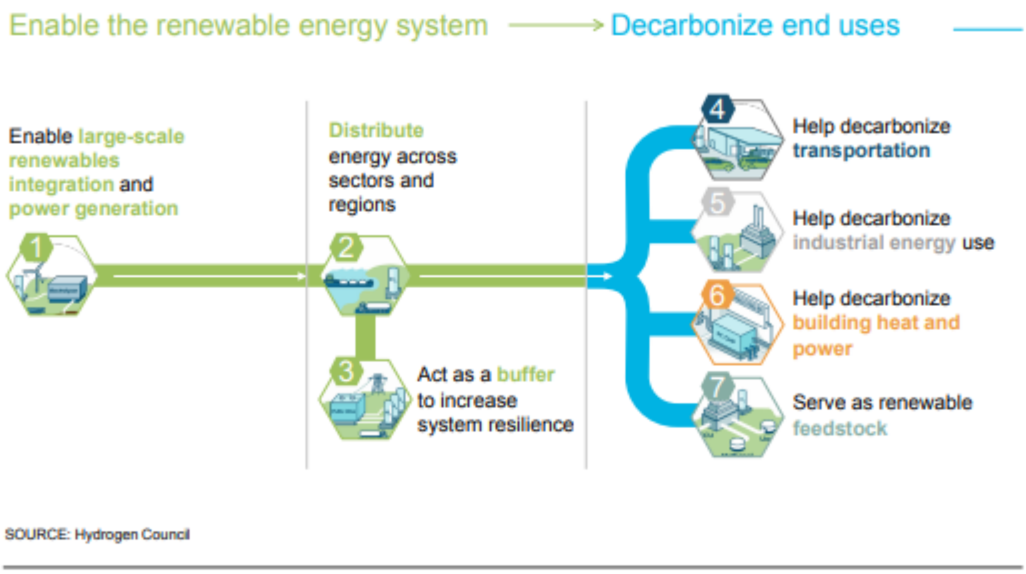


Figure 1: Hydrogen can balance energy production and use in location and time, and decarbonize end uses (HydrogenCouncil, 2017)

Hydrogen and electricity grid infrastructures together with large scale seasonal hydrogen storage and small-scale day-night electricity storage, in mutual co-existence, will be essential to realise a sustainable, reliable, zero-emission and cost-effective energy system.

Europe has a unique opportunity to realize a green hydrogen system

Europe and the neighbouring regions have good renewable resources and the industry to quickly and cost effectively realise a green hydrogen system. Europe has also a need and demand for hydrogen to decarbonise the industry, mobility and building sector. And Europe has its natural gas infrastructure. By converting part of the existing gas infrastructure for transport and storage of hydrogen will give Europe an unique opportunity to deliver on its commitments for renewable energy production and usage while utilising this current vast infrastructure asset. It will provide the European hydrogen industry a competitive advantage to produce sustainable and circular products and services while creating many green jobs at the same time.

Europe has good renewable energy resources

In Europe, good renewable energy resources are geographically distributed. However, they are not evenly distributed among EU Member States and, therefore, large-scale, pan-European energy transport and storage is necessary.

Large scale on- and offshore wind can be produced at competitive and subsidy-free prices in several parts of Europe (Vattenfall, 2019) (Guardian, 2019). Large-scale offshore wind has great potential in the North Sea, Irish Sea, Baltic Sea and parts of the Mediterranean Sea. And large-scale onshore wind potential can be found in Greece, the UK, Ireland and in many other coastal areas in Europe such as Portugal, Poland and Germany. Large-scale solar PV can nowadays also be built competitively and subsidy-free (Energylivenews, 2019), most notably in Southern Europe, for instance in Spain, Portugal, Italy and Greece.

Furthermore, low cost hydropower electricity can be produced in Iceland, Norway, Sweden, Austria, Switzerland, amongst others and geothermal electricity in Iceland, Italy, Poland and Hungary. Although, the potential expansion of the hydropower and geothermal capacity is limited, the future introduction of marine/tidal energy converters could furthermore augment the production of renewable electricity and hydrogen in the UK, Portugal, Norway and Iceland.

Ukraine has good wind resources together with a large potential for biomass. These resources could be both used for green hydrogen production together with green CO_2 production from biomass (UkrainianHydrogenCouncil, 2019).

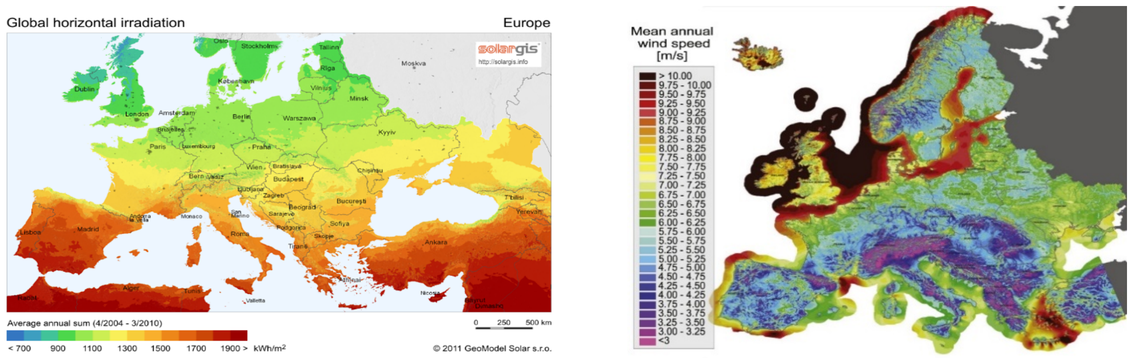


Figure 2: Solar irradiation (left) and wind speed at 80 m height (right) in Europe

Very good renewable energy resources in North-Africa and Middle East

In North Africa, however, the solar energy resources are even better than in Southern Europe. The Sahara Desert is the world's sunniest area year-round. It is a large area (at 9.4 million square km more than twice the size of the European Union) that receives, on average, 3,600 hours of sunshine yearly and in some areas 4,000 hours (Varadi, Wouters, & Hoffmann, 2018). This translates into solar insolation levels of 2,500-3,000 kWh per square meter per year. A fraction (8-10% of the Sahara Desert's area could generate the globe's entire energy demand (van Wijk, van der Roest, & Boere, 2017).

It should be noted that the Sahara Desert is one of the windiest areas on the planet, especially on the west coast. Average annual wind speeds at ground level exceed 5 m/s in most of the desert and it reaches 8-9 m/s in the western coastal regions. Wind speeds increase with height above the ground, and the Sahara winds are quite steady throughout the year. Also, Egypt's Zaafarana region is comparable to Morocco's Atlantic coast, with high and steady wind speeds (Wijk, Wouters, Rachidi, & Ikken, 2019). In Morocco, Algeria, Tunisia, Libya and Egypt certain land areas have wind speeds that are comparable to offshore conditions in the Mediterranean, Baltic Sea and some parts of the North Sea.

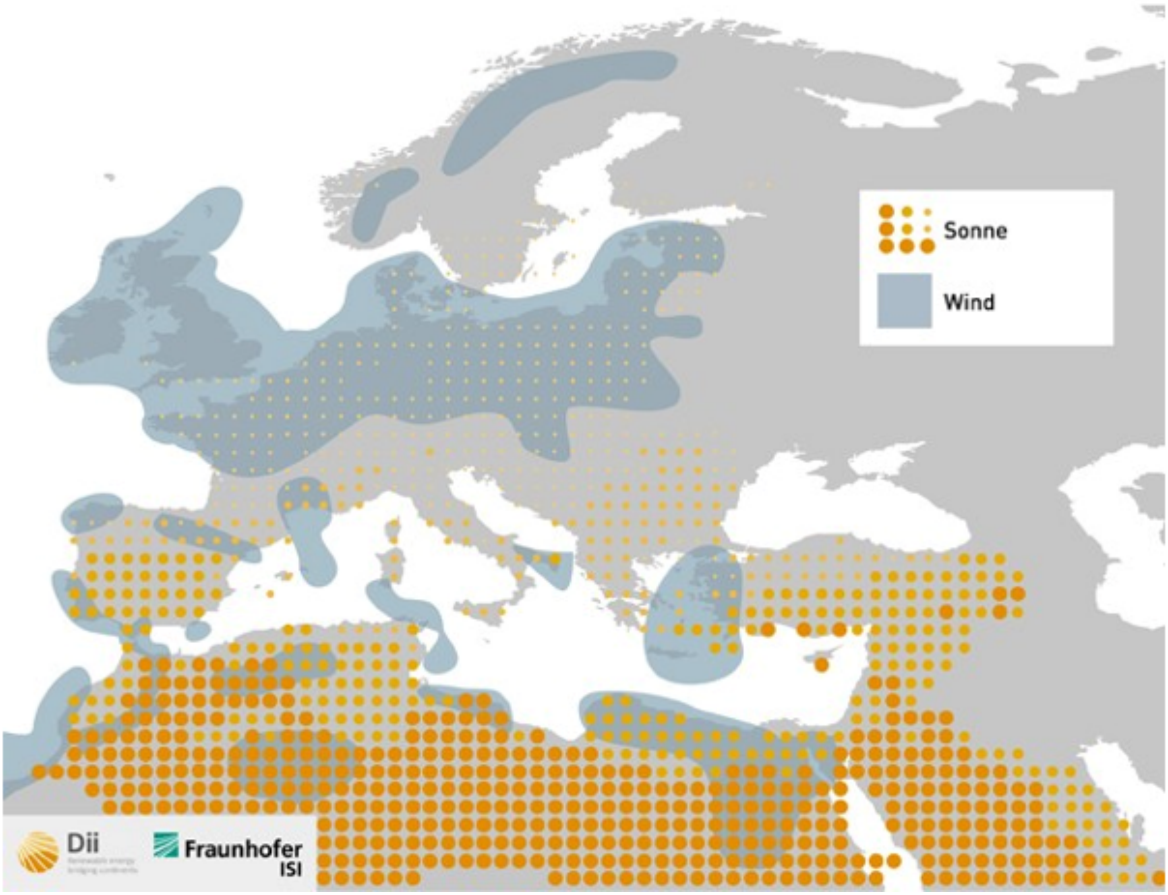


Figure 3: Solar irradiation and wind speed resources in Europe and North Africa (Dii & FraunhoferISI, 2012)

Not only North-Africa has good solar and wind resources, but also the Middle East has excellent solar resources and at some places also very good wind resources. Turkey, Oman, Saudi Arabia, Jordan, United Arab Emirates and other countries in this region could potentially become major green hydrogen exporting countries.

Europe has an increasing demand for hydrogen

Europe is an industrialised region with a major petrochemicals and chemicals industry that produces about 6 to 15% of the total global refining and chemicals output. Most of the hydrogen currently produced is used as a feedstock to make other materials. European hydrogen demand was about 325 TWh hydrogen in 2015, mainly used in refineries and in the chemical industry for the production of ammonia and methanol. Most of the hydrogen used in these industries currently comes from natural gas by Steam Methane Reforming whereby the CO2 is released to the air, so-called grey hydrogen (FCHJU, 2019).

It is expected that the current use of hydrogen as feedstock will grow. But also new opportunities for hydrogen use as feedstock are emerging. Especially in steel production hydrogen can replace coal. And hydrogen together with CO_2 can be used to produce synthetic fuels, such as kerosene. Next to the use of hydrogen as feedstock, hydrogen can be used in industry to produce high temperature heat and steam, replacing natural gas and coal. High temperature heat can be produced from hydrogen by retrofitting existing gas turbines, furnaces and boilers.

Hydrogen-powered vehicles are now available in the large car, taxi, van, bus, truck, forklifts and tractor markets. Their market shares will increase rapidly in the next decades. However, in other transportation markets, such as trains, ships, planes and drones, hydrogen will gain market share too. Fuel cells will become the dominant technology in future, whereby hydrogen will be chemically converted into electricity that drives an electric motor.

In Buildings hydrogen can be used for heating and power. Hydrogen can be used in boilers to produce heat. Hydrogen boilers and hydrogen ready boilers (boilers that can now be fuelled on natural gas and in the future on hydrogen) have entered the market in 2019. Next to these boilers, also small fuel cell micro CHP (Combined Heat and Power) installations enter the market. These micro CHP fuel cells provide both electricity and heat to buildings.

Finally hydrogen is needed in balancing the electricity system. Hydrogen can be stored and transported cheaply and easily and is therefore very suited to match electricity supply and demand in time and place. Hydrogen can be used like natural gas in existing modestly retrofitted power plants, in both the gas turbines and boilers. In future fuel cells can be used to balance the power system, both centralized as well as decentralized peak power or CHP plant.

The FCHJU (Fuel Cell Hydrogen Joint Undertaking) has released in January 2019 the report ‘Hydrogen Roadmap Europe, A sustainable pathway for the European Energy Transition’ (FCHJU, 2019). This report makes the case that achieving the energy transition in the EU will require hydrogen at large scale. Without it, the EU would miss its decarbonization objective. An ambitious roadmap for the use of hydrogen in Europe in the different sectors is considered necessary to keep global warming “well below 2 degrees Celsius above preindustrial levels. Already in 2030 the use of hydrogen will be more than doubled to 665 TWh, compared to 2015 use, see figure 4.

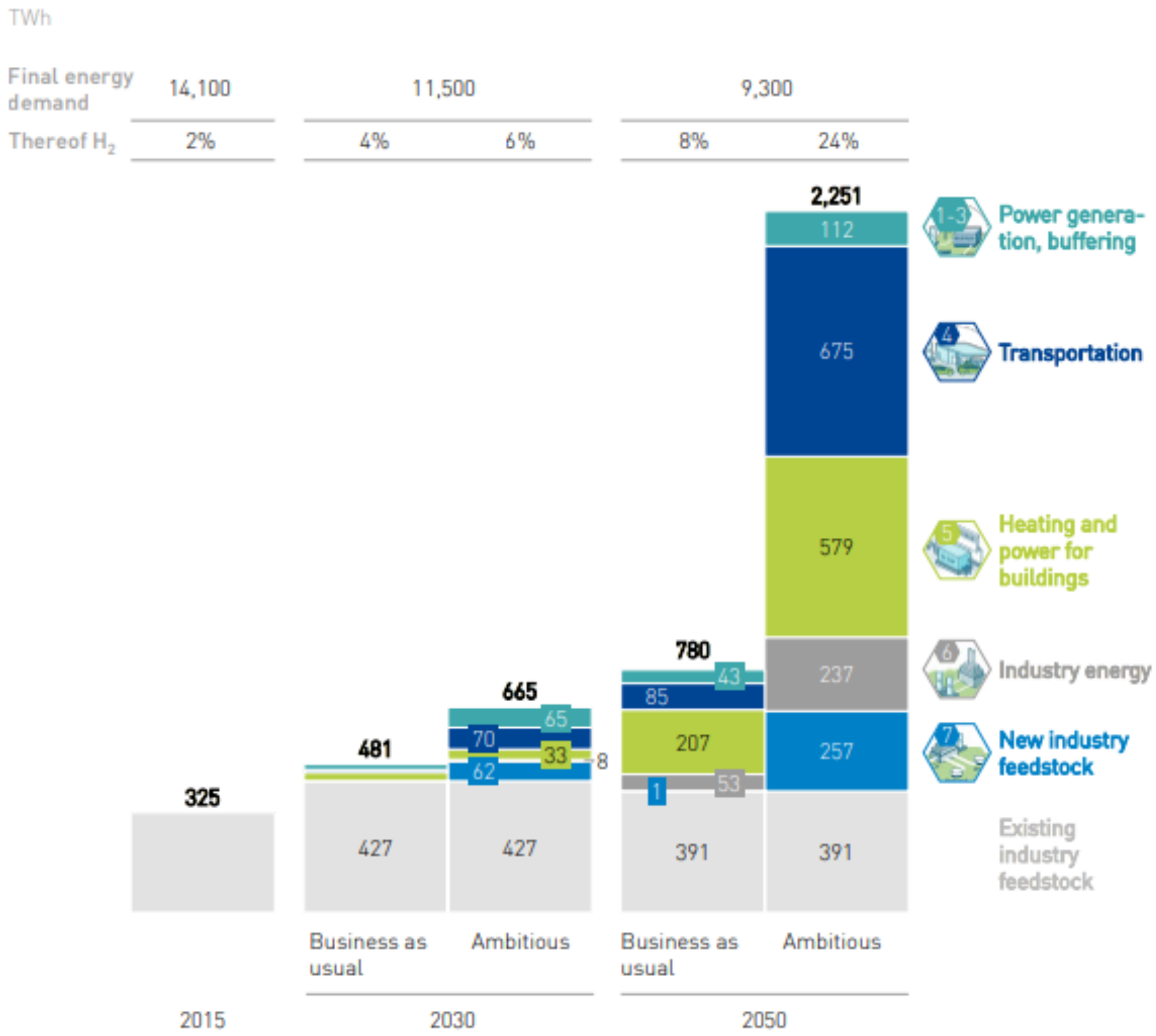


Figure 4: An ambitious roadmap for the deployment of hydrogen in the European Union as outlined in 'Hydrogen roadmap Europe, a sustainable pathway for the European Energy Transition (FCHJU, 2019)

Europe can use its sophisticated gas infrastructure to transport and store hydrogen

A challenge for the fast expansion of renewable electricity capacity in Europe is the limited electricity grid capacity. In 2018, close to €1 billion of renewable on- and offshore wind electricity in Germany was curtailed because of capacity constraints in the electricity grid (Bundesnetzagentur, 2019).

Part of the solution to integrating large amounts of renewable energy into the energy system without necessarily requiring massive electricity grid upgrades is the conversion to hydrogen.

A well-developed gas infrastructure is in place connected to the gas production regions in Europe (North Sea, Norway and the Netherlands) and outside Europe (Russia, Algeria, Libya). The energy transmission capacity in the gas infrastructure is at least a factor of 10 larger than the capacity of the electricity grid.

Re-use the natural gas pipelines to transport hydrogen

The existing gas infrastructure can be relatively easily and fast converted to accommodate hydrogen at modest cost (DNV-GL, 2017) (Kiwa, 2018). In addition, building "new" gas infrastructure is 10-20 times cheaper than building the same energy transport capacity with a "new" electricity infrastructure (Vermeulen, 2017). However, to unlock the wind resources in the Baltic Sea and the wind plus solar resources in Greece, new hydrogen pipeline infrastructure needs to be realised.

In the Netherlands Gasunie, the Dutch natural gas transmission grid operator, has already started to realise a hydrogen backbone pipeline infrastructure, by converting natural gas pipelines. This hydrogen backbone connects hydrogen production sites, among others from offshore wind at the North Sea, to hydrogen storage in salt caverns and to the demand in industrial clusters, see figure 5. Gasunie has already converted a 12 km natural gas pipeline into a hydrogen pipeline that is operational since November 2018 (Gasunie, 2018).

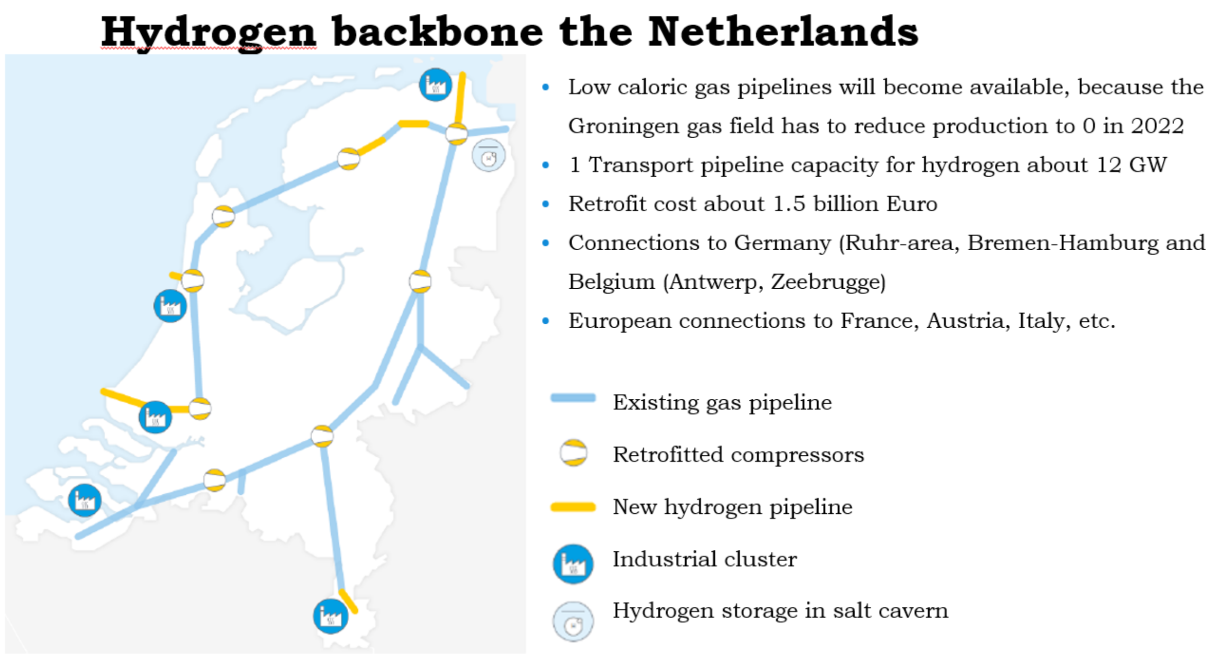


Figure 5: ***Hydrogen Backbone the Netherlands*** *– One natural gas transport pipeline infrastructure will be converted into a hydrogen transport pipeline that connects hydrogen production to hydrogen storage and the demand in industrial clusters* (Gasunie, 2019)

Also in Germany, FNB Gas, the cooperation of the large national gas transport companies in Germany, has developed a plan for a 5.900 kilometre hydrogen transport grid, partly by converting existing natural gas pipelines, to connect future hydrogen production centres in northern Germany, with large scale hydrogen storage in salt caverns and to the large customers in the west and south, see figure 6.

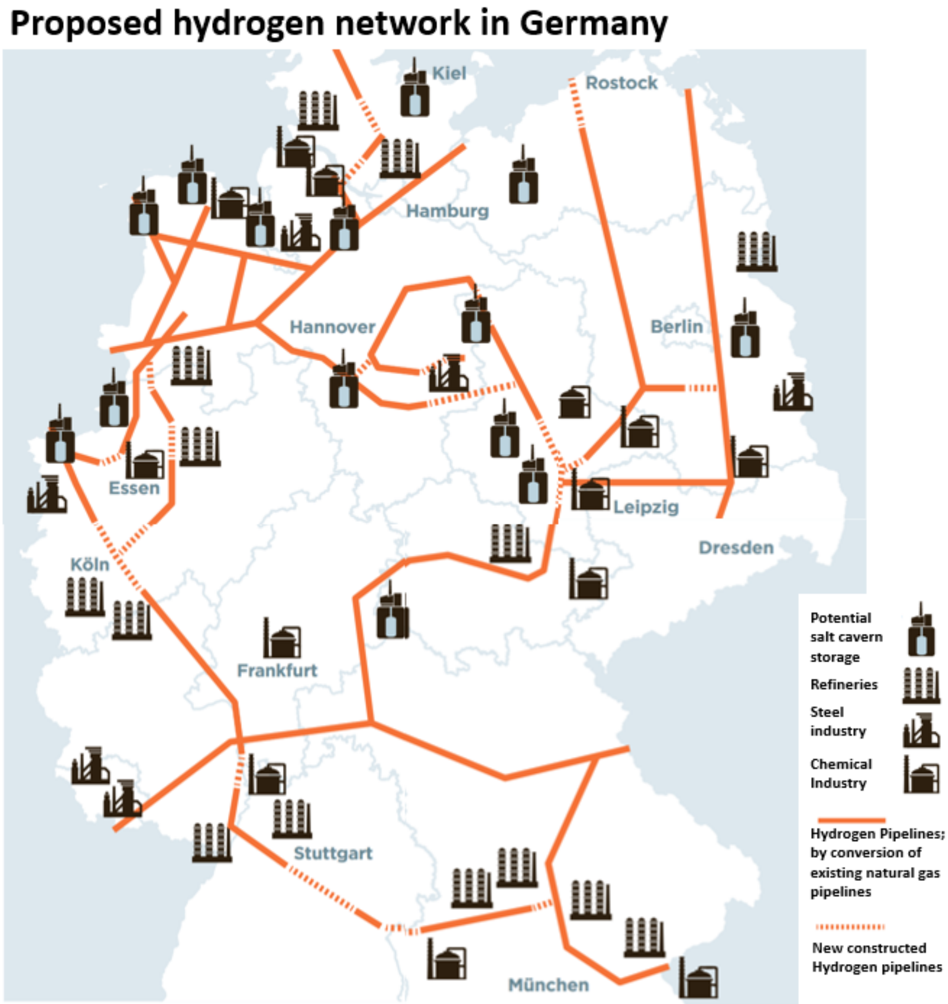


Figure 6: ***Hydrogen Backbone in Germany*** *– proposed by FNB Gas, the cooperation of the large national gas transport companies in Germany, to develop a 5.900 kilometre hydrogen transport grid throughout Germany (Figure copied from German newspaper Handelsblatt 28-1-2020* (Stratmann, 2020)*).*

A transnational European hydrogen gas infrastructure backbone that can transport large amounts of hydrogen from the solar and wind resource areas throughout Europe is outlined in figure 7. Besides green hydrogen, also blue hydrogen (hydrogen from fossil fuels, whereby the CO_2 is captured and stored) could be fed into this backbone hydrogen infrastructure, whereby blue hydrogen could create the large volumes of hydrogen, necessary to respond to the large demand centres and initiate the fast conversion of the natural gas infrastructure into a hydrogen infrastructure.

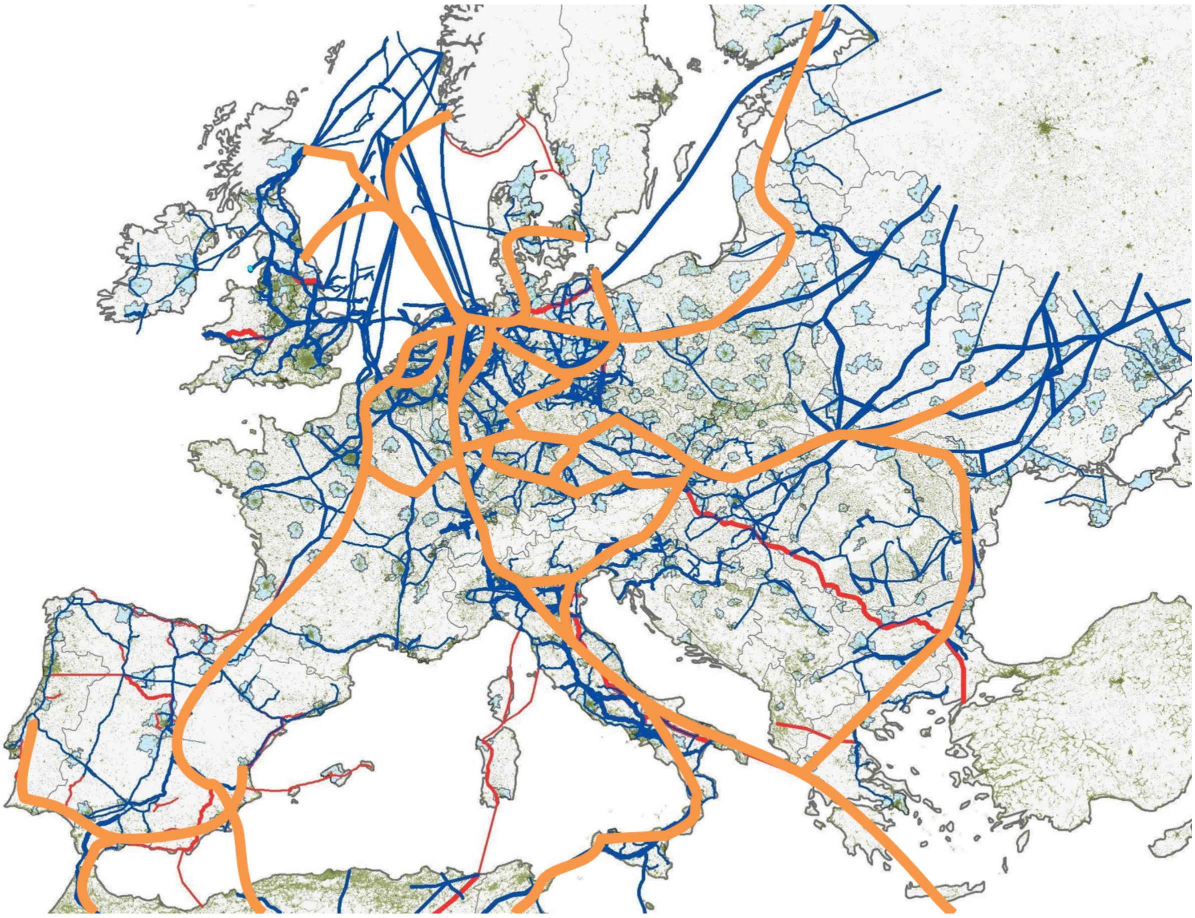


*Figure 7: **European Transnational Hydrogen Backbone -** The natural gas infrastructure in Europe (blue and red lines) and an outline for a hydrogen backbone infrastructure (orange lines). The main part of the hydrogen backbone infrastructure consists of re-used natural gas transport pipelines with new compressors. A ''new'' hydrogen transport pipeline must be realised from Italy to Greece and from Greece to the Black See, also along the South Coast of the Iberian Peninsula a dedicated hydrogen pipeline has to be realized.*

Realize new hydrogen transport infrastructure, especially between Africa and Europe

North Africa has even better solar resources together with interesting wind resources. Today Europe imports natural gas from Algeria and Libya, with several pipeline connections to Spain and Italy. For Europe it would be very interesting to unlock the renewable energy potential in North Africa, convert this electricity to hydrogen and transport the energy via pipelines to Europe. Part of the natural gas grid could be converted to hydrogen (Wijk, Wouters, Rachidi, & Ikken, 2019). But also, the construction of new hydrogen pipelines would be a cost-effective option to transport renewable energy to Europe, see figure 8. The realisation of a large new hydrogen pipeline from Egypt, via Greece to Italy, 2,500 km, with 66 GW capacity, consisting of 2 pipelines of 48 inch each, would imply an investment of € 16.5 billion. With a load factor of 4,500 hours per year, an amount of 300 TWh or 7.6 million ton hydrogen per year can be transported. The levelized cost for hydrogen transport by such a pipeline is calculated to be 0.005 €/kWh or 0.2 €/kg H_2, which is a reasonable fraction of the total cost of delivered hydrogen (vanWijk, 2019).

Figure 8: ***Europe North-Africa Hydrogen Backbone*** *– The Natural gas infrastructure between North-Africa and Europe (grey lines) and an outline for a first phase hydrogen backbone infrastructure (orange lines). The main part of the hydrogen backbone infrastructure consists of re-used natural gas transport pipelines with new compressors. A ''new'' hydrogen transport pipeline must be realized from Italy to Greece, crossing the Mediterranean Sea to Egypt, which could eventually be extended to the Middle East* (Wijk, Wouters, Rachidi, & Ikken, 2019).

Availability of salt caverns for large scale hydrogen storage

Natural gas demand in Europe, especially in Northern Europe, shows a strong seasonal variation, in wintertime the gas demand is 2-3 times higher than in summertime (BDEW, 2018) (Entrance, 2017). However, natural gas production is constant throughout the year. Therefore, large scale seasonal storage of natural gas is necessary. Natural gas is stored in large quantities in empty gas fields, porous rock formations and salt caverns. About 15-20% of the total gas consumption is stored to balance gas production and consumption (Timmerberg & Kaltschmitt, 2019) (vanWijk, 2019).

Storage of natural gas is today also crucial to balance electricity supply and demand. Balancing the electricity system is done by pumped hydropower storage but mainly by flexible power plants, especially gas fired power plants.

Salt caverns are the "left over" of salt production. A number of these salt caverns are in use for natural gas storage and in some other caverns oil, compressed air and other products are stored, see figure 9. Salt caverns can be used to store hydrogen in the same way as they can store natural gas (HyUnder, 2013). Already salt caverns are in use to store hydrogen for many decades, for example near Leeds in the UK.

In a typical salt cavern, hydrogen can be stored at a pressure of about 200 bar. The storage capacity is then about 6,000 ton hydrogen or about 240 GWh. The total installation costs, including piping, compressors and gas treatment, are about € 100 million (Michalski, et al., 2017). For comparison, if this amount of energy would be stored in batteries, with costs of 100 €/kWh, the total investment cost would be € 24 billion. Storing energy as hydrogen in salt caverns is therefore at least a factor of 100 cheaper that storing energy as electricity in batteries.

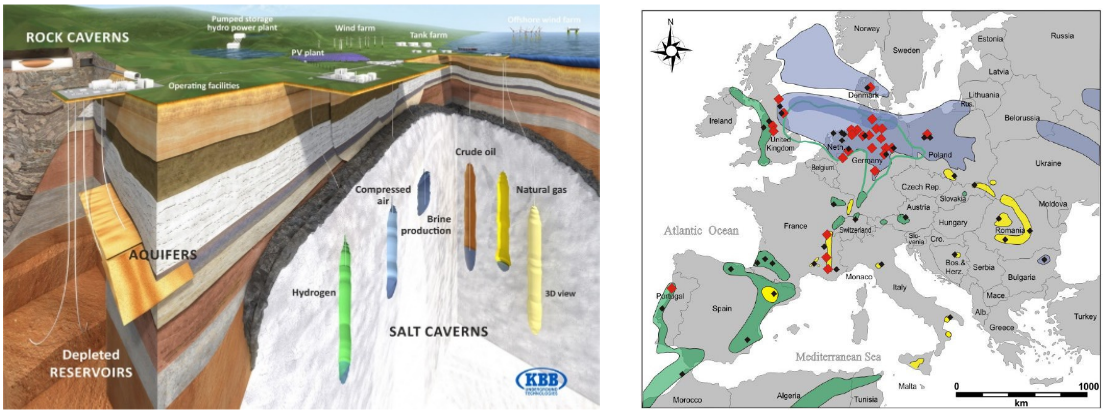


Figure 9: Salt cavern (right) and salt formations with salt caverns throughout Europe (left). The red diamonds are salt caverns in use for natural gas storage

Europe has still many empty salt caverns available for large scale hydrogen storage. Besides dedicated salt caverns for hydrogen, new storage capacity can be developed in the different salt formations in Europe. A recent study shows that there is a very large hydrogen storage potential in salt caverns in Europe, see figure 10 (Caglayan, et al., 2019). And maybe hydrogen can be stored in some empty gas fields that meet specific requirements to store hydrogen. However, this needs more research.

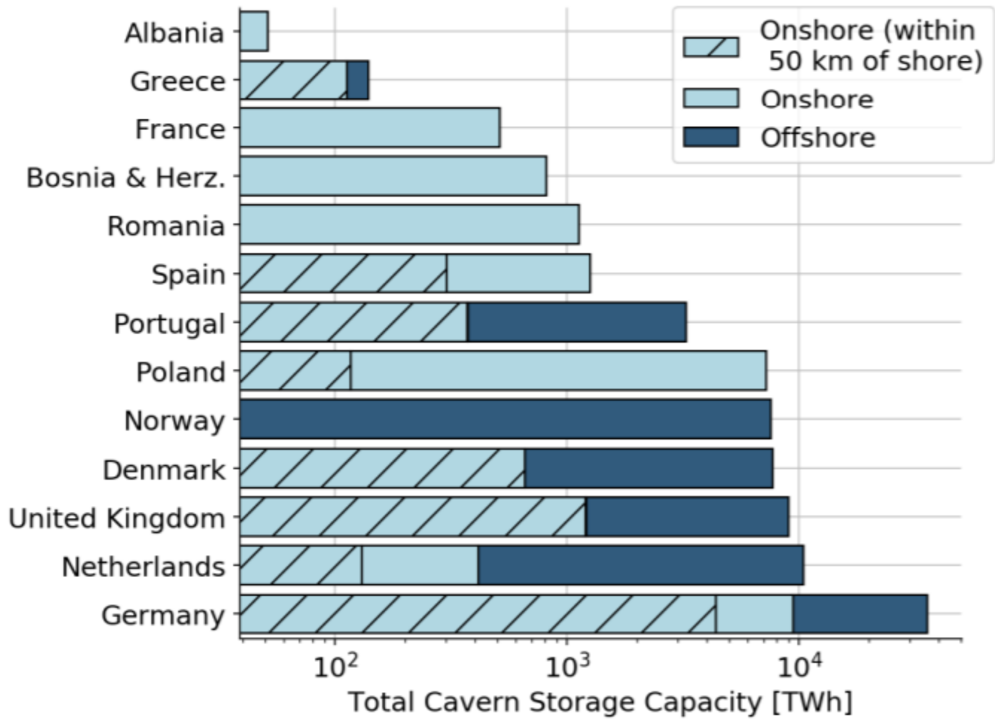


Figure 10: Salt cavern hydrogen storage potential in Europe (Caglayan, et al., 2019)

How can the infrastructure transition take place from natural gas to hydrogen?

The difficult question is, how can the transition take place from a natural gas infrastructure to a hydrogen infrastructure. Because at first there is not enough hydrogen production to build or retrofit a natural gas pipeline into a hydrogen transport pipeline with a capacity of 15-20 GW. So retrofitting a natural gas transport pipeline into a hydrogen pipeline or to build a new dedicated hydrogen pipeline is only relevant and cost effective at the end of the period up to 2030.

There are several possible pathways and solutions for this transition from natural gas to hydrogen.

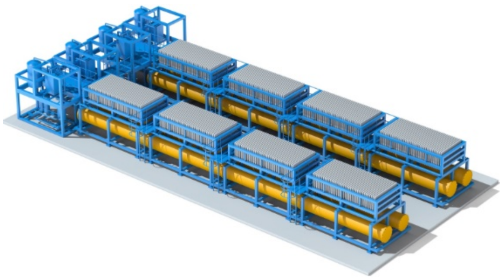
- Produce as soon as possible also large quantities of carbon neutral hydrogen to have enough hydrogen volume to fill a transport pipeline. This makes it possible to convert natural gas pipelines to hydrogen transport pipelines earlier.
- Blend hydrogen in natural gas. Most probably 2-5% of hydrogen could be blended in the transport natural gas grids without the need to replace compressors. Above 5% the hydrogen could be blended in, in one specific transport pipeline, where the compressors are replaced.
- Put a small hydrogen pipe in a natural gas pipeline. Such a pipe in pipe system is most probably cheaper and faster to install. In this way 1-2 GW capacity of hydrogen can be transported over larger distances, f.e. crossing the Mediterranean Sea or at the North Sea, without exceptional high cost. And at the same time still natural gas can be transported.
- Build extra Ammonia plants in harbor areas and export the hydrogen by shipping the ammonia. This ammonia could be used in the fertilizer and chemical industry, it could be cracked back to hydrogen or it could be used direct as a fuel in diesel engines in sea ships.
- Build Hydrogen liquefaction plants in harbor areas and export liquid hydrogen by shipping. The liquid hydrogen could be converted into gases hydrogen easily in the port of arrival and put into a pipeline system. Or the liquid hydrogen could be put into a truck that transport the liquid hydrogen to fueling stations (up to 10 times more energy can be transported in liquid hydrogen than at pressurized hydrogen)
- Other solutions to ship hydrogen, such as binding to toluene, re-use CO_2 to convert to methanol, formic acid, kerosene, or another synthetic hydrocarbon.

The type of solution that will be preferable will depend on the regional characteristics. For example at the North Sea, where natural gas pipelines are available, blending or pipe in pipe solutions are most probably a more preferable option. But in Morocco most probably converting to ammonia and shipment of ammonia could be the preferred option. Therefore the transition from natural gas to a hydrogen infrastructure, developing harbor areas for hydrogen, distribution of hydrogen to fueling stations and buildings and cross border import/export of hydrogen are topics that needs more thorough research to come up with clever and cost effective solutions.

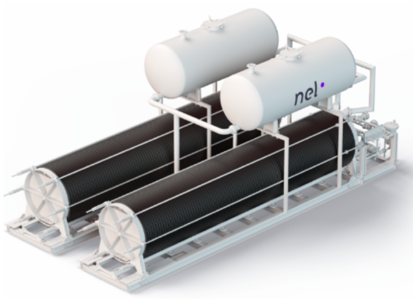
Europe has a world class electrolyser industry for green hydrogen production

Hydrogen is an energy carrier, like electricity and it must be produced from an energy source. It can be (electro)chemically processed from fossil energy sources, such as gas, oil, coal or fossil electricity, or from renewable resources, such as biogas, biomass, green electricity or direct from sunlight. Hydrogen produced from biogas, biomass and hydrogen produced via electrolysis from water with renewable electricity is called **renewable** or **green** hydrogen. In the electrolyser technology, Europe has a strong market position and is globally leading.

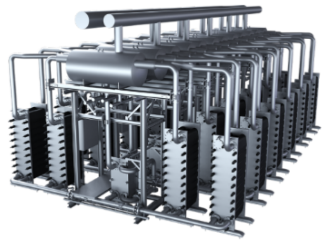
Although there is little dedicated hydrogen production via water electrolysis today, electrolysers are not a new technology. Today worldwide about 20-25 GW of electrolyser capacity is operated mostly for chlorine production. By electrolysis of salt dissolved in water, chlorine is produced from the salt, but at the same time hydrogen is produced from water. Hydrogen is a by-product, that is partly used to produce heat or steam. Globally, a large part of these chlorine electrolysers has been produced by European companies and therefore the electrolyser industry and supply chain in Europe have today a strong world market position. This is a good starting position to build a leading water electrolyser industry in Europe. Some examples of European electrolyser products are shown in figure 11.



Alkaline electrolyser ThyssenKrupp

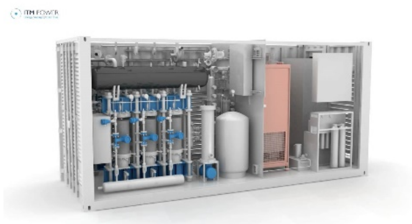


Alkaline electrolyser NEL

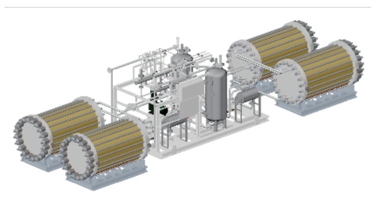


PEM electrolyser Siemens

PEM electrolyser Hydrogenics



PEM electrolyser ITM Power



Alkaline electrolyser McPhy

Figure 11: Electrolyser products from Europe.

The “2x40 GW Green Hydrogen Initiative”

The realisation of a renewable hydrogen economy will create jobs, economic growth and welfare for Europe, North-Africa, Ukraine and other neighbouring areas. At the same time, it could contribute to a cleaner, decarbonised Europe and Africa. However, such a hydrogen economy requires a coordinated European approach in collaboration with Africa and their neighbouring regions such as the Middle-East. Such an approach must encompass renewable (and low-carbon or blue) hydrogen production, where the hydrogen market development is combined with the development of a hydrogen infrastructure.

In many countries, including Japan, China, US, South Korea, Australia and Canada, there is a strong increase in budgets for hydrogen research, innovation and implementation. Especially Japan has a very strong commitment to realise a hydrogen economy, showing its engagement to the world through the Olympic Games 2020, which will be labelled the hydrogen games. Most notably Japan, China and Canada have emerging renewable hydrogen equipment manufacturing industries that are competing with European ones.

The European electrolyser industry and supply chain has a strong and competitive world market position today. If the European Union wants to create a world leading electrolyser industry for renewable hydrogen production, the time to act is now.

Therefore we propose to install 40 GW electrolyser capacity in the countries of the European Union as well as 40 GW electrolyser capacity in neighbouring countries, especially in North-Africa and Ukraine.

We, the European industry, are committed to develop a strong and world-leading electrolyser industry and market and to commit to produce renewable hydrogen at equal and eventually lower cost than low-carbon (blue) hydrogen. A prerequisite for that is that a 2x40 GW electrolyser market in the European Union and neighbouring countries (North-Africa and Ukraine) will develop up to 2030.

Roadmap 2x40 GW Green Hydrogen production to 2030

Today the installed capacity for water electrolysis in the EU is limited. In the past years, a tremendous effort has been delivered by electrolyser companies, with support from the EU, to bring down cost, increase efficiency, increase electrolyser unit size and build up production volumes. Pilot and demo projects have been installed, but the time is now to scale up the electrolyser market in order to bring down cost and to develop a strong and competitive European electrolyser industry.

Most present hydrogen production is at or close to the sites where the hydrogen is consumed. Hydrogen demand is currently only prevalent where hydrogen is used as a feedstock, e.g. in the chemical and petrol-chemical industry. There is only a limited, privately owned hydrogen pipeline infrastructure between some chemical and petrochemical industries and areas. The current hydrogen production is therefore characterised as captive, there is no public large-scale hydrogen pipeline infrastructure available and other than point to point sales, there is no regular and existing hydrogen market and infrastructure.

In the near future there will be a renewable and low-carbon hydrogen market for feedstock to produce chemicals, petrochemicals, new synthetic fuels (i.e. kerosene) and to produce “green steel” from iron-ore in a reduction process called direct reduce iron by using hydrogen instead of carbon monoxide. Next to these industrial feedstock applications a hydrogen market for mobility, high and low temperature heat and electricity production for balancing purposes will emerge.

Low-carbon and renewable hydrogen production can be either captive (near the hydrogen demand) or in central locations (near the energy resource). Today, captive solutions include low-carbon hydrogen that will be produced by converting natural gas with carbon capture, supplied by a natural gas pipeline and renewable hydrogen that can be produced by water electrolysis, whereby the electricity is supplied using the electricity grid. Due to electricity grid capacity restrictions, the electrolyser capacity at most of these sites is limited to maximum several hundred MWs.

Captive Market; Hydrogen production near the hydrogen demand

In the near future, a hydrogen market for transport fuels will emerge. At hydrogen fuelling stations, hydrogen can be produced locally using water electrolysis on-site. The renewable electricity can be supplied by the electricity grid or locally produced from solar or wind turbines. Electrolyser capacities up to 10 MW can produce enough hydrogen to supply such a hydrogen refuelling station. Also, hydrogen can be supplied to these refuelling stations by truck or pipeline. Nowadays, compressed hydrogen is transported by truck to the hydrogen refuelling stations, but in the future, when demand increases, liquid hydrogen will be an option.

The 1-10 MW scale market for electrolysers at hydrogen fuelling stations will grow in the coming decade. Next to this, the market for electrolysers to produce part of the renewable hydrogen for the chemical industry, refineries and steel production, requiring capacities in the 10-200 MW range, will grow. These hydrogen markets for industry and mobility might remain captive markets in the near future, hydrogen will be produced on-site, where it is used. The electrolyser is connected to the electricity grid to produce (near) baseload hydrogen.

Hydrogen Market; Hydrogen production near the energy resource

However, to fully decarbonise the chemical and steel industry multi-GW electrolyser capacity is needed, which cannot be installed near these plants due to insufficient electricity grid capacities. Besides, there is a need for hydrogen in other markets such as mobility, for high and low temperature heating and for electricity production (especially for electricity balancing purposes) which need to be supplied from central hydrogen production sites. The GW electrolyser market, therefore, will have a different market structure. The GW electrolysers will be installed near or close to large scale wind, solar, hydro and/or geothermal electricity production locations. The hydrogen will be fed into a gas grid, preferably a 100% hydrogen grid, that will transport and distribute the hydrogen to all kinds of consumers, industry, mobility, houses, buildings and balancing power plants. Because these electrolysers are connected to renewable electricity production, the electrolysers will not produce in baseload, the load factor depends on the renewable electricity production.

The GW electrolyser market requires a European hydrogen market design, with flexible and hybrid market regulation mechanism’s that gives possibilities to Transmission System Operators’ (TSO) and Distribution System Operators’ (DSO) (Energy transport and distribution companies) for (early) market creation. Nevertheless in an early phase of the market development, a framework that enables and supports the roll-out of power to gas investments by any players, as a non-regulated activity should be part of a policy framework for hydrogen.

Large volumes of low-carbon and renewable hydrogen produced at or nearby the resource locations, will be fed into a hydrogen grid. Grid companies, TSO's and DSO's, need to have the obligation to connect hydrogen producers and customers to such a hydrogen infrastructure. Also, hydrogen storage facilities need to be developed and connected to this hydrogen infrastructure, guaranteeing supply of hydrogen to customers at all times, independent of seasonal) variations of renewable electricity. With a certification system, the EU can create a market for renewable, low-carbon hydrogen. So, these GW scale electrolysers will produce hydrogen for a hydrogen market.

When a hydrogen pipeline infrastructure are established, also electrolysers in the range of 10-100 MW could be installed near small and medium scale renewable electricity production locations. If not enough electricity grid capacity is available to connect solar or wind farms to the electricity grid, part of the solar or wind electricity could be converted to hydrogen and fed into the hydrogen grid. Such a hybrid connection to an electricity and hydrogen grid, could alleviate the capacity constraints in the electricity grid and absorb the electricity at moments when the electricity demand is lower than the production.

The market design of such a European hydrogen market can learn from the natural gas market design, but needs to have the flexibility to convert from electricity to hydrogen and vice-versa, with distinct roles for producers, TSOs and DSOs, independent regulators and clear rules for grid access, pricing, clearing, gas quality, safety etc.

Roadmap 40 GW electrolyser capacity in the European Union to 2030.

A roadmap for the development towards 40 GW electrolyser capacity in the EU by 2030 is depicted in table 1. The total hydrogen production in 2030 by this 40 GW will be 4.4 million ton hydrogen, 1 million ton by the 6 GW captive electrolyser capacity and 3.4 million ton by 34 GW hydrogen market electrolyser capacity. The 4.4 million ton hydrogen (173 TWh) represents 25% of the total EU hydrogen demand (665 TWh), as presented in the Hydrogen Roadmap Europe (FCHJU, 2019). This will ensure Europe's leading position in the emerging global hydrogen economy, which is crucial to become and remain a leader in this emerging technology.

Electrolyser Capacity MW	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total 2030
Captive Market												**6,000**
Chemical	5	20	45	130	200	200	250	300	350	400	450	2,350
Refineries	10	40	50	100	100	100	200	200	300	300	400	1,800
Steel			20	30	50	100	100	100	100	150	150	800
Other (glass, ceramics)		10	20	30	40	50	50	50	50	50	50	400
Hydrogen refuelling stations	10	20	30	40	50	60	70	80	90	100	100	650
Hydrogen Market												**34,000**
Centralised GW scale			200	500	1,000	2,000	3,000	4,000	5,500	7,000	8,500	31,700
Decentralised 10-100 MW scale	10	20	40	70	110	160	220	290	370	460	550	2,300
TOTAL (MW)	**35**	**110**	**405**	**900**	**1,550**	**2,670**	**3,890**	**5,020**	**6,760**	**8,460**	**10,200**	**40,000**

Table 1: A roadmap to 40 GW electrolyser capacity in the European Union 2030 shows the development of both a captive market (6 GW) and a hydrogen market (34 GW).

A roadmap to 40 GW electrolyser capacity in the EU in 2030 shows both a 6 GW captive and a 34 GW hydrogen market. This 40 GW electrolyser capacity will produce 4.4 million ton or 173 TWh hydrogen in 2030, representing 25% of the total EU hydrogen market in 2030.

Hydrogen Roadmap Europe, January 2019

Roadmap 40 GW electrolyser capacity in North-Africa and Ukraine 2030.

North-Africa has very favourable solar and wind resources, while Ukraine has good wind, solar and biomass resources. Both have also space available for large scale renewable energy production and have the potential to produce the necessary renewable energy for their own use as well as to become a large-scale net exporter of renewable energy. Both North-Africa and Ukraine are neighbouring regions to the European Union, which makes it possible and favourable to transport hydrogen via pipelines to the EU. Because hydrogen transport by pipeline is cheaper than transport by ship, this has a competitive advantage.

In North-Africa and the Ukraine the hydrogen production will be close to large scale renewable electricity production sites. An interesting and feasible use of green hydrogen in North-Africa and Ukraine is for ammonia/fertilizer production. We estimate that up to 2030 an electrolyser capacity of 7.5 GW can be installed close to the ammonia/fertilizer production. With this installed capacity, in

North-Africa, about 3 million ton “green ammonia” could be produced in Egypt, Algeria and Morocco and in Ukraine it is expected that 1 million ton “green ammonia” could be produced.

The other part of the 40 GW, about 32.5 GW electrolyser capacity will be installed for large scale hydrogen production, eventually fed into a hydrogen pipeline, for export. Roughly about 3 million ton (118 TWh) could be hydrogen export to the EU in 2030, representing 17% of the total EU hydrogen demand in 2030, as presented in the Hydrogen Roadmap Europe (FCHJU, 2019). A roadmap for the development towards 40 GW electrolyser capacity in North-Africa and Ukraine is depicted in table 2.

By developing this electrolyser capacity in cooperation between the EU and North-Africa/Ukraine the European electrolyser industry could develop an important export market, which is crucial to become and remain a leader in this emerging technology.

Electrolyser Capacity MW	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total 2030
Domestic Market												**7,500**
Ammonia North-Africa				75	125	250	500	750	1,000	1,250	1,500	5,450
Ammonia Ukraine					50	100	200	250	300	400	500	1,800
Other (glass, steel, refineries)							10	20	30	40	50	150
Hydrogen refueling stations								10	20	30	40	100
Export Market												**32,500**
Hydrogen North-Africa					500	1,000	2,000	3,000	4,000	6,000	8,000	24,500
Hydrogen Ukraine						500	700	1,000	1,400	1,900	2,500	8,000
TOTAL (MW)				**75**	**675**	**1,850**	**3,410**	**5,030**	**6,750**	**9,620**	**12,590**	**40,000**

Table 2: A roadmap to 40 GW electrolyser capacity in North Africa and Ukraine 2030 shows the development of a domestic market (7.5 GW) and an export market (32.5 GW).

A roadmap to 40 GW electrolyser capacity in North Africa and the Ukraine in 2030 shows both a 7.5 GW domestic market and a 32.5 GW export market. The domestic market is mainly for ammonia production while the export market is mainly export by pipeline to the EU, about 3 million ton or 118 TWh hydrogen in 2030, representing 17% of the total EU hydrogen market in 2030.

Hydrogen Roadmap Europe, January 2019

Renewable hydrogen becomes cost competitive

Alkaline electrolysers are considered a mature technology, currently used to produce chlorine. PEM electrolysers are going through a steep learning curve. Both alkaline and PEM electrolysers can be used for water electrolysis to produce hydrogen. These electrolyser technologies consist of electrolyser cells that are combined to build an electrolyser stack. To build a GW scale electrolyser, a number of electrolyser stacks are placed in parallel. Both electrolyser technologies are expected to achieve remarkable technology improvements in the next decade. Amongst others, higher efficiencies, less degradation, higher availability, larger cell sizes, higher operating pressure, less critical material use together with overall reduced material use, will reduce hydrogen production cost by electrolysers.

However, next to these technology improvements, especially installed capacity volume and plant size will bring down the electrolyser cost. An electrolyser plant has a similar technology structure as a solar power plant. Both electrolysers and solar plants are built by producing cells, assembling a number of cells to a solar-module/electrolyser-stack and installing a number of modules/stacks to realize the required plant capacity. Although different, a comparable cost reduction process similar to solar power plants can be foreseen for electrolyser plant. Automated production of the electrolyser cell components, cells and stacks will bring down the cost for the electrolyser stacks and building GW scale electrolyser plants will reduce the balance of plant costs per kW. The balance of plant costs are the costs for compressors, gas cleaning, demineralised water production, transformers and the installation cost. A substantial electrolyser market volume together with realizing GW scale electrolysers, are essential drivers for significant cost reductions (IEA, 2019).

The electrolyser plant costs are important, but the dominant factor in the hydrogen production cost is the electricity price, determining 60-80% of the hydrogen cost. Therefore, it is very important that the cost of renewable electricity is as low as possible. But also important for cost reduction is to realise large scale integrated renewable electricity-hydrogen production plants. Integrated renewable electricity-hydrogen production can reduce cost, due to technology integration, e.g. avoiding AC-DC and DC-AC conversion costs plus losses and due to business integration, e.g. integrated project development, construction, but also reducing transaction cost, permitting costs, electricity grid costs and taxes.

Altogether, technology developments, capacity volume, GW scale, low renewable electricity production cost and integrated renewable electricity-hydrogen production will result in renewable hydrogen produced by electrolysers becoming competitive with low-carbon hydrogen around 2025. Low-carbon hydrogen produced from natural gas by SMR (Steam Methane Reforming) or ATR (Auto Thermal Reforming) with CCS (Carbon Capture and Storage) is assumed to cost between 1,5-2,0 Euro/kg.

Hydrogen price 1 Euro/kg equals

- 7 Euro/GJ H_2
- 0.025 Euro/kWh H_2
- 0.09 Euro/m^3 H_2
- 0.24 Euro/m^3 natural gas equivalent

Renewable hydrogen becomes competitive with grey hydrogen after 2030. But around 2030, renewable hydrogen will be competitive with grey hydrogen together with a 20-30 Euro per ton CO_2 price (1,2- 1,8 Euro/kg H_2). When hydrogen is produced from natural gas, every 10 Euro per ton CO_2 adds about 0,1 Euro/kg to the hydrogen price.

In North-Africa, the electricity production cost with solar and wind will be most probably lower than in Europe, because of the better solar and wind resources and cheaper land cost. Therefore, the hydrogen production cost will be lower than in Europe. But the hydrogen from North-Africa must be transported by pipeline or ship to Europe. Large-scale long-distance hydrogen pipeline transport will add about 0.2 Euro per kg hydrogen, which will level out the lower hydrogen production cost in North-Africa. Transport by ship is more expensive that pipeline transport. However in future, hydrogen import from North-Africa will certainly be competitive with hydrogen production in Europe.

If a 2 X 40 GW electrolyser market in the European Union, North Africa and Ukraine, to be realised in the period up to 2030, will be created, the electrolyser industry will commit themselves to the Capex, Opex and efficiency developments as presented in table 3.

Hydrogen production by electrolysers*	Capex (euro/kW)	OPEX %/yr Capex	System Efficiency (HHV)	Electricity (4.000-5.000hr) (euro/MWh)	Hydrogen (euro/kg)
Till 2020	600-700	2%	70-75%	40-50	3,0-4,5
2020-2025	400-600	1,5%	75-80%	30-40	2,0-3,0
2025-2030	300-500	1%	80-82%	25-30	**1,5-2,0**
After 2030	<300	<1%	>82%	20-30	1,0-1,5

*Hydrogen production cost for hydrogen delivered at 30 bar pressure and 99,99% purity

Table 3: Green Hydrogen production cost development up to 2030. Around 2025 green hydrogen production cost will become competitive with blue hydrogen production cost; 1.5-2.0 Euro/kg. Around 2030 green hydrogen will become competitive with grey hydrogen, with 20-30 Euro/ton CO_2 price; 1,2-1,8 Euro/kg

GW scale electrolysers at wind-solar electricity-hydrogen production sites will produce renewable hydrogen at competitive cost with low-carbon hydrogen (1,5-2,0 Euro/kg) in 2025 and with grey hydrogen, with 20-30 Euro/ton CO_2 price (1,2-1,8 Euro/kg) in 2030.

Investment in 2x40 GW electrolyser capacity

Based on the roadmaps for electrolyser capacity development in Europe and North-Africa-Ukraine and the developments for the electrolyser Capex cost as depicted in table 3, the total electrolyser investments can be calculated. These total investments in 2 X 40 GW electrolyser capacity are between 45-25 billion Euro. The higher estimate is based on the high Capex figures given in table 3. The lower estimate is based on the lower Capex figures given in table 3. According to the roadmaps, over 85% of all electrolyzer capacity will be realized in the period 2025-2030, which explains the relative low total investment costs.

Total investment in 2x40 GW electrolyser capacity is between 25 and 45 billion Euro

What we offer and what we need

We, the industry, are committed to developing a strong and world leading electrolyser industry and supply chain and commit to realising 2x40 GW electrolyser capacity by 2030 in Europe, North Africa and Ukraine. But we need the European Union and its member states to design, create and facilitate a hydrogen market, infrastructure and economy.

2x40 GW Green Hydrogen Initiative European Union 2030

What we offer

- Significant reduction in electrolyser costs
- Renewable hydrogen competitive with low-carbon hydrogen, in 2025 and with grey hydrogen with 20-30 Euro/ton CO_2 price, in 2030
- GW scale electrolyser and components production facilities in Europe
- Investment ready and bankable technology and projects
- Investments in 2X40 GW Electrolyser Capacity
- Increased industry budgets for hydrogen related research and innovation
- More green jobs
- Realizing faster and cheaper integration of large-scale renewable electricity
- By importing cheap renewable hydrogen, a competitive sustainable energy system can be realized cheaper and faster.
- A world leading and competitive electrolyser and renewable hydrogen industry

What we need

- Hydrogen market design, with flexible and hybrid market regulation.
- Implementation in EU energy policies, regulations and standards
- Hydrogen Infrastructure by converting part of the natural gas infrastructure
- Open access to public hydrogen infrastructure
- Access to financial sector, banks, pension funds, EIB, investment funds, EU funds (IPCEI Infrastructure fund, and others)
- Large scale hydrogen storage facilities
- Substantial hydrogen R&D and innovation budgets
- Hydrogen market stimulation programs
- EU auctions and tenders for renewable electricity-hydrogen production
- A new, unique and long-lasting mutual cooperation on political, societal and economic level between the EU and North Africa needs to be designed and realized.

There is a unique opportunity for the EU to develop a green hydrogen economy which will contribute to economic growth, create jobs and to a sustainable, affordable and fair energy system. Building on this position, the EU can become the world market leader for electrolysers and green hydrogen production.

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Appendix
Hydrogen for Climate Action

IPCEI (Important Project of Common European Interest) on Hydrogen

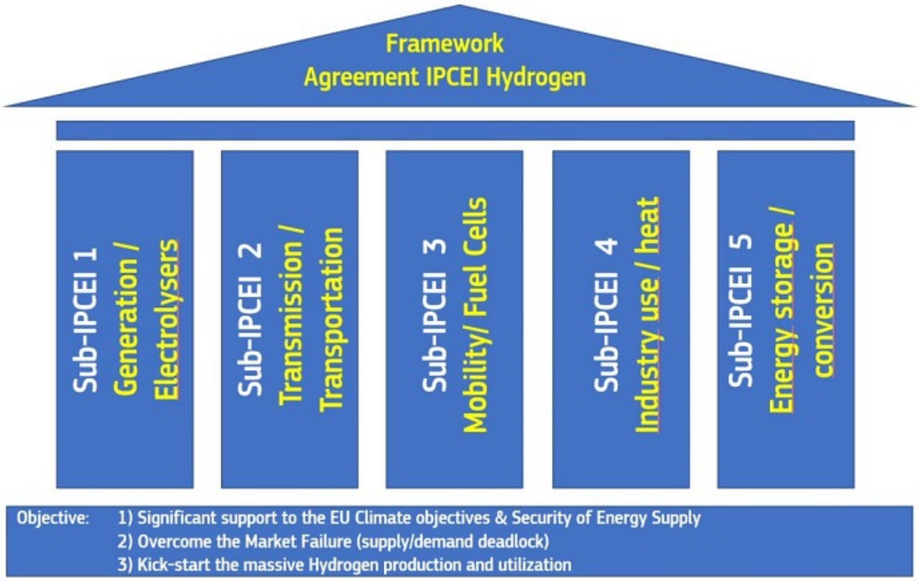
https://www.hydrogen4climateaction.eu/

Hydrogen has been selected by the European Commission as a strategic value chain and is therefore undergoing a process of managing one or several IPCEI's on hydrogen. The link between the existing gas infrastructure and the TEN-T corridors for mobility would create an excellent basis to develop hydrogen demand for both the industry as well as for mobility

An IPCEI on Hydrogen is being prepared since October 2019. This includes a significant number of projects in all the areas important for Hydrogen such as

- **Generation of green Hydrogen** from Renewable Energy Sources using Electrolysers
- **Transportation of Hydrogen** through trucks and railway tube trailers, cargo ships and pipelines in various packaging forms (liquefied, pressurized, LOHC, NH3, etc)
- the **Mobility sectors** using Fuel Cells in heavy duty vehicles (HDVs), public busses, trains, barges, seagoing vessels, etc. including Hydrogen Refuelling Stations (HRS) on roads, ports and bus depots
- **Industry applications** such as green Steel, Fertilizers, Cement, or production of industrial heat for many production sectors (mixed with natural gas in varying percentages), as well as refineries and Hydrogen use in the chemical sector
- **Energy Sector** applications such as Temporary and Seasonal Storage, utilization of curtailed energy to off-load the electricity grid, generators for electricity production from excess hydrogen
- In the **Housing sector** for Combined Heat and Power (CHP) applications, replacing natural gas in specific applications
- In **end user driven applications** such as supermarket chains wishing to green their logistics or cruise ship lines trying to accommodate customer wishes for clean travel

Many of the technologies behind are well developed, but applications are as of today not yet commercially viable, because of the supply demand dead-lock which does not bring the hydrogen prices down to the necessary level at the desired locations to drive big volume applications. In order to break that deadlock, a kick-start for the involved technologies and a massive investment in green hydrogen production is necessary.



List of Hydrogen IPCEI projects (as of November 2019)

- Green Octopus
- Green Spider
- Zero emission Urban Delivery @ rainbow Unhycorn
- White Dragon
- H2Go
- The Orange Camel
- Hybrit
- Black Horse
- Blue Dolphin
- Green Hydrogen @ Blue Danube
- Silver Frog