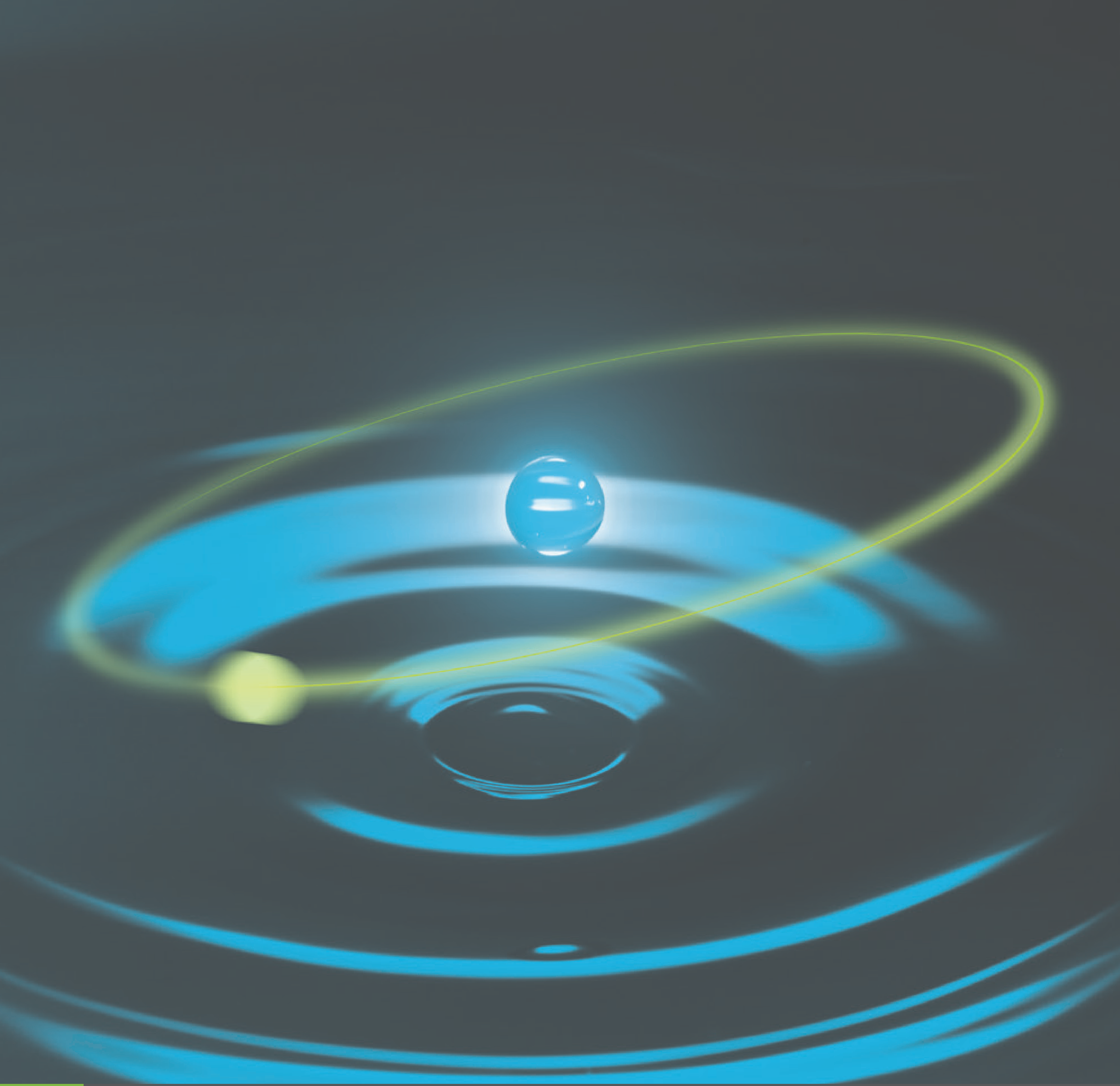

# Green Hydrogen for a European Green Deal A 2x40 GW Initiative

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# SUMMARY


Hydrogen will play a pivotal role in achieving an affordable, clean and prosperous economy. Hydrogen allows for cost-efficient bulk transport and storage of renewable energy and can decarbonise energy use in all sectors.

The European Union together with North Africa, Ukraine and other neighbouring countries have a unique opportunity to realise a green hydrogen system. Europe including Ukraine has good renewable energy resources, while North Africa has outstanding and abundant resources. Europe can re-use its gas infrastructure with interconnections to North-Africa and other countries to transport and store hydrogen. And Europe has a globally leading industry for clean hydrogen production, especially in electrolyser manufacturing.
If the European Union, in close cooperation with its neighbouring countries, wants to build on these unique assets and create a world leading industry for renewable hydrogen production, the time to act is now. Dedicated and integrated multi GW green hydrogen production plants, will thereby unlock the vast renewable energy potential.

We, the European hydrogen industry, are committed to maintaining a strong and world-leading electrolyser industry and market and to producing renewable hydrogen at equal and eventually lower cost than low-carbon (blue) hydrogen. A prerequisite is that a 2x40 GW electrolyser market in the European Union and its neighbouring countries (e.g. North Africa and Ukraine) will develop as soon as possible.

A roadmap for 40 GW electrolyser capacity in the EU by 2030 shows a 6 GW captive market (hydrogen production at the demand location) and 34 GW hydrogen market (hydrogen production near the resource). A roadmap for 40 GW electrolyser capacity in North Africa and Ukraine by 2030 includes 7.5 GW hydrogen production for the domestic market and a 32.5 GW hydrogen production capacity for export.

If a 2x40 GW electrolyser market in 2030 is realised alongside the required additional renewable energy capacity, renewable hydrogen will become cost competitive with fossil (grey) hydrogen. GW-scale electrolysers at wind and solar hydrogen production sites will produce renewable hydrogen cost competitively with low-carbon hydrogen production (1.5-2.0 €/kg) in 2025 and with grey hydrogen (1.0-1.5 €/kg) in 2030.

By realizing 2x40 GW electrolyser capacity, producing green hydrogen, about 82 million ton $CO_2$ emissions per year could be avoided in the EU. The total investments in electrolyser capacity will be 25-30 billion Euro, creating 140,000-170,000 jobs in manufacturing and maintenance of 2x40 GW electrolysers.

The industry needs the European Union and its member states to design, create and facilitate a hydrogen market, infrastructure and economy. Crucial is the design and realisation of new, unique and long-lasting mutual co-operation mechanisms on political, societal and economic levels between the EU and North Africa, Ukraine and other neighbouring countries.

The unique opportunity for the EU and its neighbouring countries to develop a green hydrogen economy will contribute to economic growth, the creation of jobs and a sustainable, affordable and fair energy system. Building on this position, Europe and its neighbours can become world market leaders for green hydrogen production technologies.

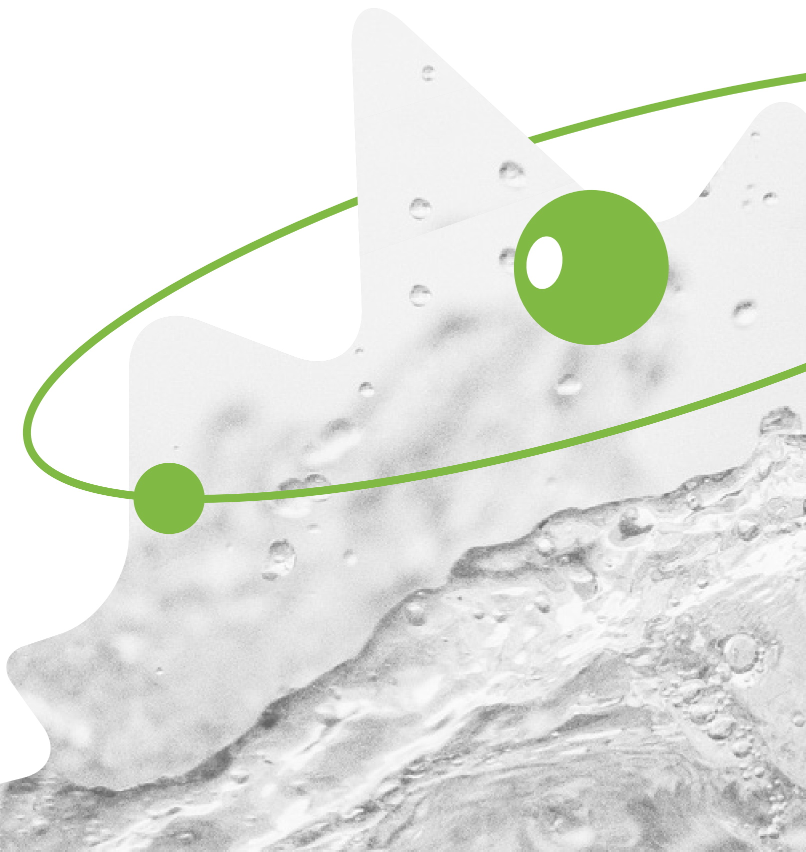
# PIVOTAL ROLE OF HYDROGEN IN A SUSTAINABLE ENERGY SYSTEM

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 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



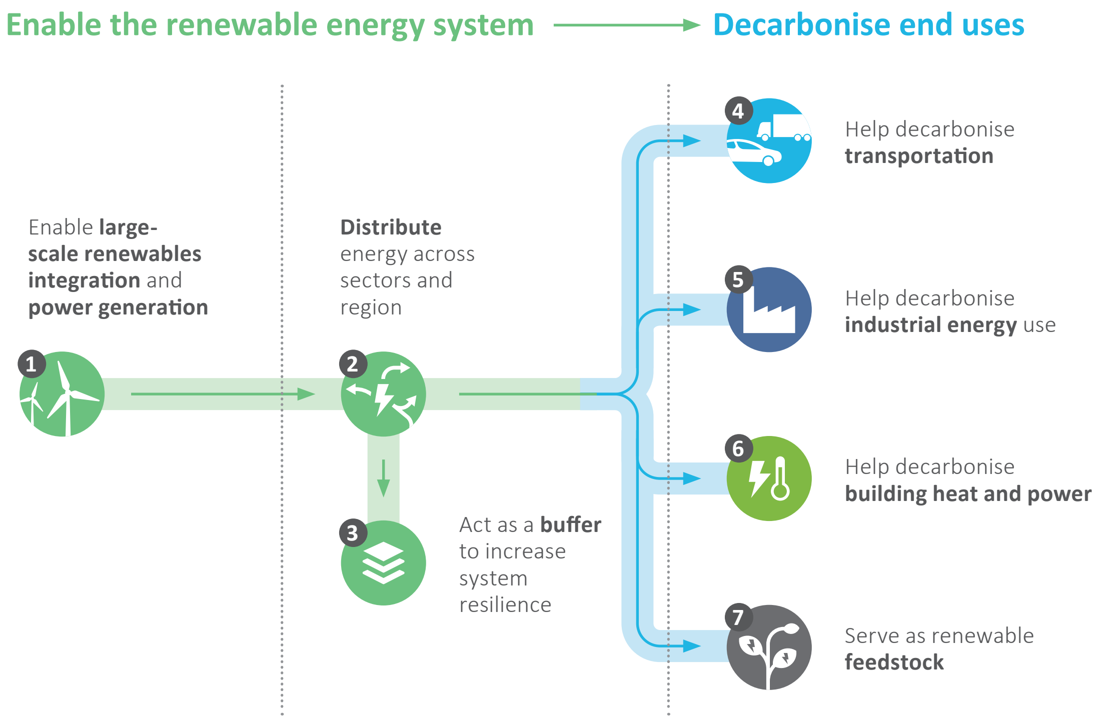
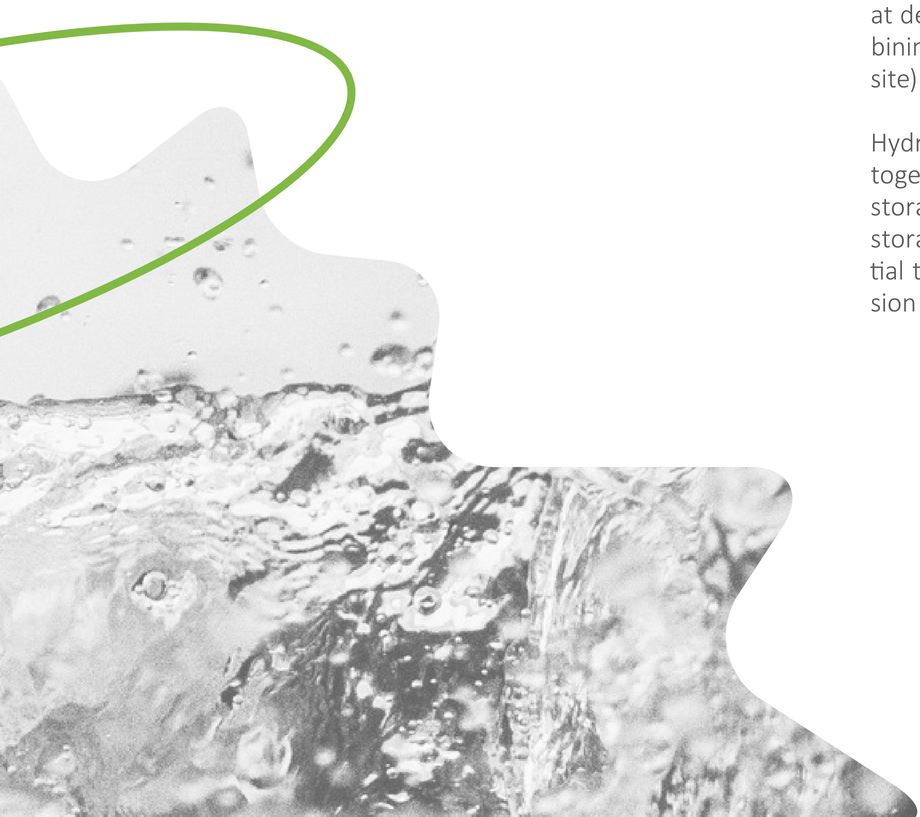



***Figure 1*** *Hydrogen can balance energy production and use in location and time, and decarbonise end uses (HydrogenCouncil, Hydrogen scaling up; a sustainable pathway to the global energy transition, 2017)*



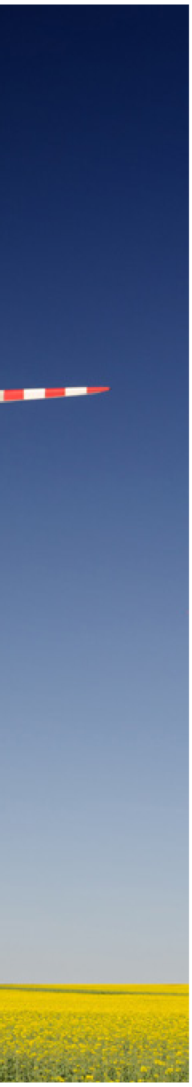
Renewable electricity continues to drop in price and will soon enable the production of hydrogen at costs lower than oil or natural gas at dedicated hydrogen production plants (combining wind and/or PV with electrolysers at one site)

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 REALISE A GREEN HYDROGEN SYSTEM

Europe and the neighbouring regions have good renewable resources and the industrial capacity to quickly and cost-effectively realise a green hydrogen system. Europe also requires considerable amounts of hydrogen to decarbonise the industry, transport and building sector.

Moreover, Europe has an extensive natural gas infrastructure. Converting part of the existing gas infrastructure for transport and storage of hydrogen will give Europe a 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.



## Increasing demand for hydrogen in Europe

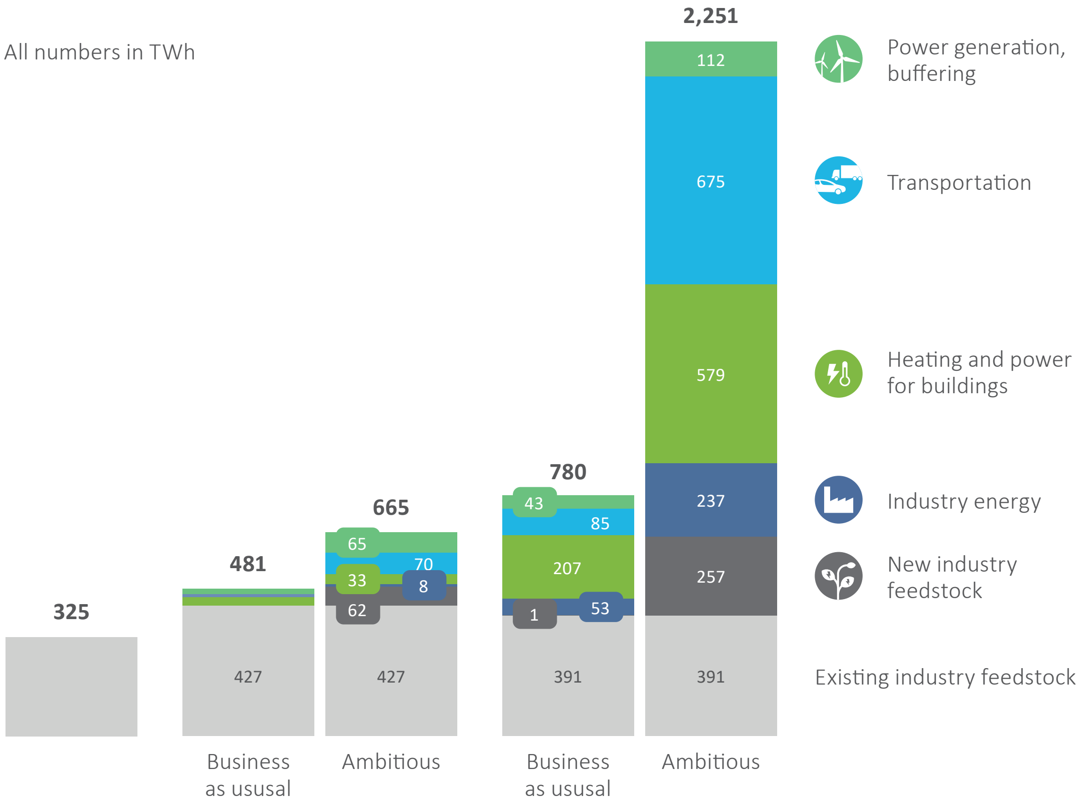
Europe is an industrialised region with major petrochemical and chemical industries that produce about 6 to 15% of the total global refining and chemicals output. Most of the hydrogen currently produced is used as a feedstock to make other materials. European hydrogen demand was about 325 TWh hydrogen in 2015, mainly used in refineries and in the chemical and agribusiness industry for the production of methanol and ammonia. Most of the hydrogen used in these industries is currently produced from natural gas through steam methane reforming. If the $CO_2$ is released to the air the hydrogen is referred to as “grey hydrogen” (FCH JU, Hydrogen Roadmap Europe, a sustainable pathway for the European energy transition, 2019).

It is expected that the current demand for hydrogen as feedstock will grow. But also new opportunities for hydrogen use as feedstock are emerging. In steel production, hydrogen can replace coal to reduce iron ore. And hydrogen together with $CO_2$ can be used to produce synthetic fuels, such as methanol and kerosene. Apart from the use of hydrogen as feedstock, hydrogen can also 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 furnaces and boilers.

Hydrogen-powered vehicles are now available in the car, taxi, van, bus, truck, forklifts and tractor markets. Their market shares will increase rapidly in the next decades. In other transportation markets, such as rail, shipping and aviation (including drones), hydrogen will gain market share too. Fuel cells will become the dominant technology in the 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 replace natural gas or oil in boilers to produce heat. Hydrogen boilers and hydrogen-ready boilers (boilers that now run 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 entered the market. These micro CHP fuel cells provide both electricity and heat to buildings. European companies such as BDR Thermea, Viessmann, Bosch and others have brought these new hydrogen appliances already to the market.

Last but not least, hydrogen is highly needed to balance 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 replace natural gas in existing power plants after minor modification, 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 plants.

The FCH JU (Fuel Cell Hydrogen Joint Undertaking) released the report ‘Hydrogen Roadmap Europe, a Sustainable Pathway for the European Energy Transition’ in January 2019 (FCH JU, 2019). This report makes the case that achieving the energy transition in the EU will require hydrogen at large scale. Without hydrogen, the EU would miss its decarbonization objective. An ambitious roadmap for the use of hydrogen in Europe in the different sectors is considered to be 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.




| 2015 | 2030 | | 2050 | | Year |
|---|---|---|---|---|---|
| 14,100 | 11,500 | | 9,300 | | **Final energy demand [TWh]** |
| 2% | 2% | 6% | 8% | 24% | **Thereof $H_2$** |

***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(FCH JU, 2019)*

## Good renewable energy resources far from the demand

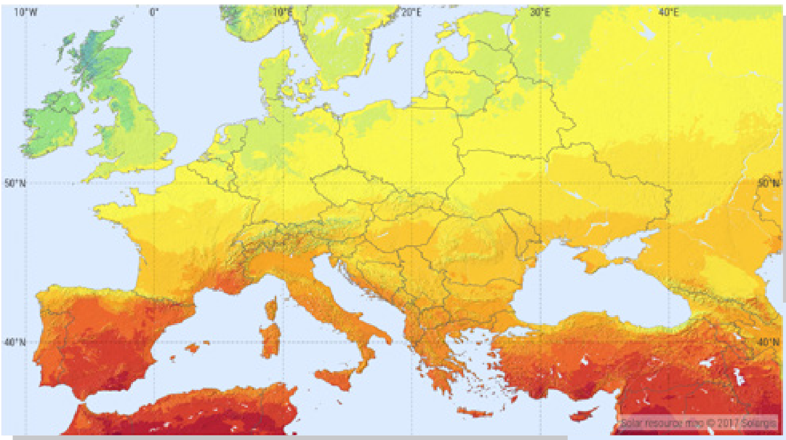
In Europe there are good solar and wind energy resources, especially in the North and South of Europe. In the neighbouring regions of North-Africa and the Middle East there are even better solar and also good wind resources. However, the areas with good resources are usually far away from the energy demand at industrial sites and cities in Europe. Conversion to hydrogen at the solar and wind farm offers the opportunity to transport the solar and wind electricity over large distances relatively cheap and without losses.

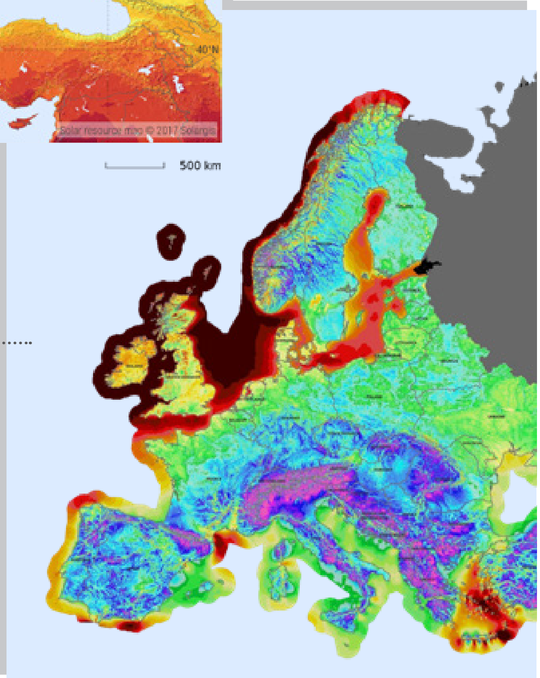
## Good renewable energy resources in Europe

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, trade and storage are 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 and 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).




**Average annual sum of PVOUT, period 1994-2016**

800 1000 1200 1400 1600 1800 kWh/kWp

**Mean Annual Wind Speed (m/s)**

| | | |
|---|---|---|
| < 3.00 | 5.25 - 5.50 | 7.75 - 8.00 |
| 3.00 - 3.25 | 5.50 - 5.75 | 8.00 - 8.25 |
| 3.25 - 3.50 | 5.75 - 6.00 | 8.25 - 8.50 |
| 3.50 - 3.75 | 6.00 - 6.25 | 8.50 - 8.75 |
| 3.75 - 4.00 | 6.25 - 6.50 | 8.75 - 9.00 |
| 4.00 - 4,25 | 6.50 - 6.75 | 9.00 - 9.25 |
| 4.25 - 4.50 | 6.75 - 7.00 | 9.25 - 9.50 |
| 4.50 - 4.75 | 7.00 - 7.25 | 9.50 - 9.75 |
| 4.75 - 5.00 | 7.25 - 7.50 | 9.75 - 10.00 |
| 5.00 - 5.25 | 7.50 - 7.75 | > 10.00 |

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

## Outstanding renewable energy resources in North-Africa and Middle East

In North Africa, the solar energy resources are even better and much more abundant 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 enjoys, 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, Solar Power to the People, 2017).

It should be noted that the Sahara Desert is also 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 (van Wijk A. , 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.

Not only North Africa has good and abundant 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 (van Son & Isenburg, 2019).

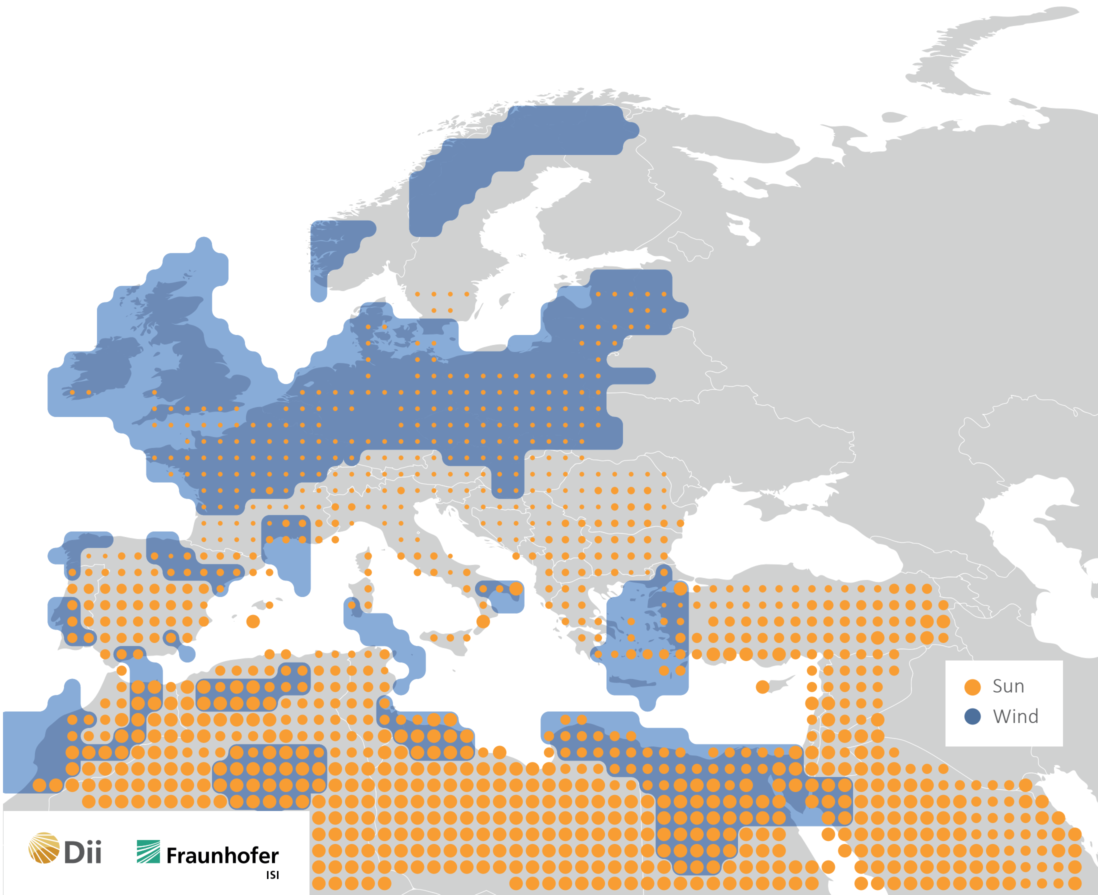



***Figure 3** Solar irradiation and wind speed resources in Europe and North Africa (Dii & FraunhoferISI, 2012)*

**Renewable energy transport and storage via hydrogen.**

The good renewable energy resources in Europe, North Africa and Middle East are located far from the European energy demand at industrial sites and cities. At these good renewable energy resources sites abundant, cheap but intermittent solar and wind electricity can be produced. The challenge now is how this energy can be transported and stored at low costs and losses. Conversion of solar and wind electricity at the production site into hydrogen offers a solution for this challenge, because transport and storage cost for hydrogen are significantly cheaper than for electricity.

Hydrogen transport cost by pipeline are about 10-20 times cheaper than electricity transport cost by a cable (Vermeulen, 2017). A fundamental difference between electricity transport by cables and hydrogen transport by pipelines is the capacity of the infrastructure. An electricity transport cable has a capacity between 1-2 GW, while a hydrogen pipeline can have a capacity between 15 and 30 GW. Besides, transporting electricity via cables incurs losses, while hydrogen transport by pipelines does not have losses. Next to the transport cost, hydrogen storage cost can be cheap. Hydrogen storage cost in salt caverns are at least a factor of 100 cheaper than electricity storage cost in batteries (van Wijk & Wouters, 2019).

Therefore, at good solar and wind resources areas multi GW solar and wind farms can be realised, producing electricity that is directly converted in hydrogen by water electrolysis. Instead of solar and wind power plants, these are solar and wind hydrogen plants. Producing cheap hydrogen at multi GW solar and wind farms, large scale hydrogen transport by pipelines and hydrogen storage in salt caverns can offer lower overall energy system cost, a reliable energy system and above all a clean, decarbonised energy system.

## Europe can use its 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 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 quickly 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 and solar resources in Greece, new hydrogen pipeline infrastructure is required.

Gasunie, a European gas infrastructure company, has started to realise a hydrogen backbone pipeline infrastructure in the Netherlands, 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 has been operational since November 2018 (Gasunie, 2018).


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

Also in Germany, FNB Gas, the association of the large national gas transport companies in Germany, has developed a plan for a 5.900 km hydrogen transmission 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.

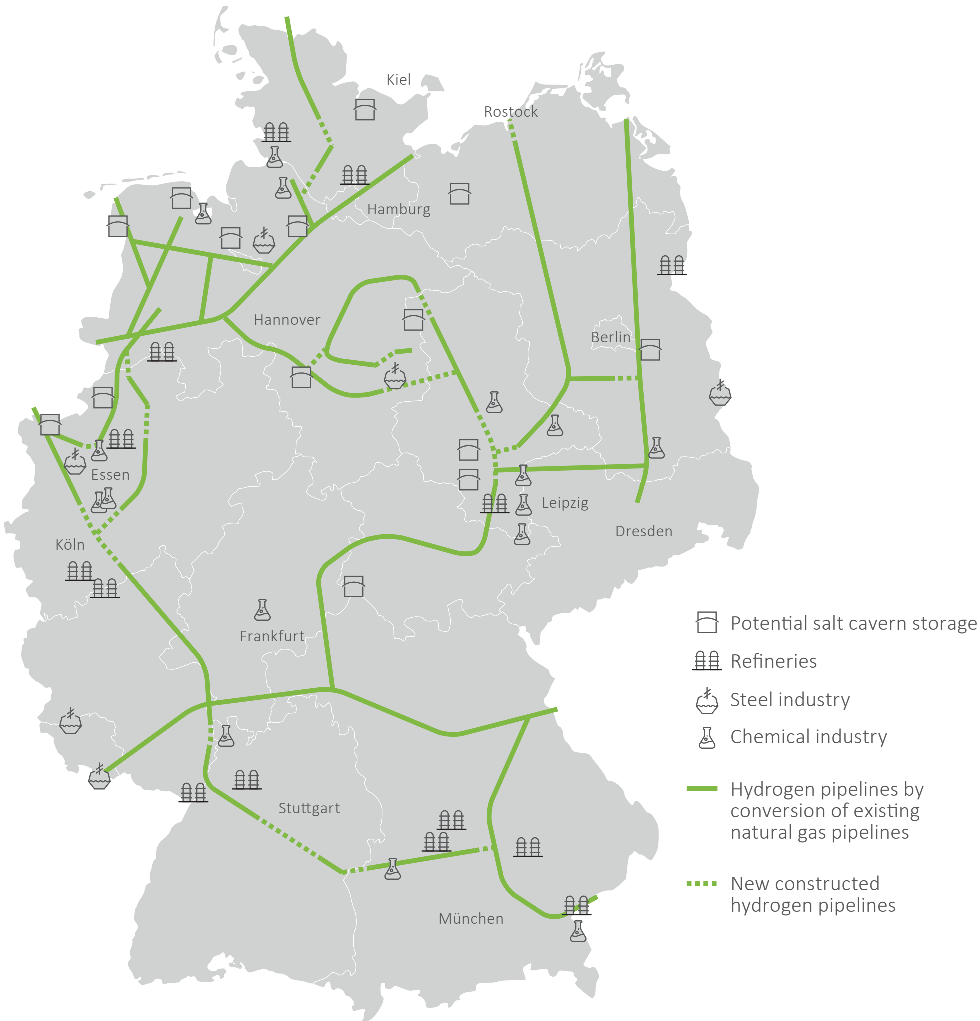



***Figure 6*** *Hydrogen Backbone in Germany – proposed by FNB Gas, the cooperation of the large national gas transport companies in Germany, to develop a 5.900 km hydrogen transport grid throughout Germany (Figure taken from German newspaper Handelsblatt 28-1-2020 (Stratmann, 2020)).*

A transnational European hydrogen gas infrastructure backbone that can transport large amounts of hydrogen from the solar and wind resource areas throughout Europe including the Ukraine 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.

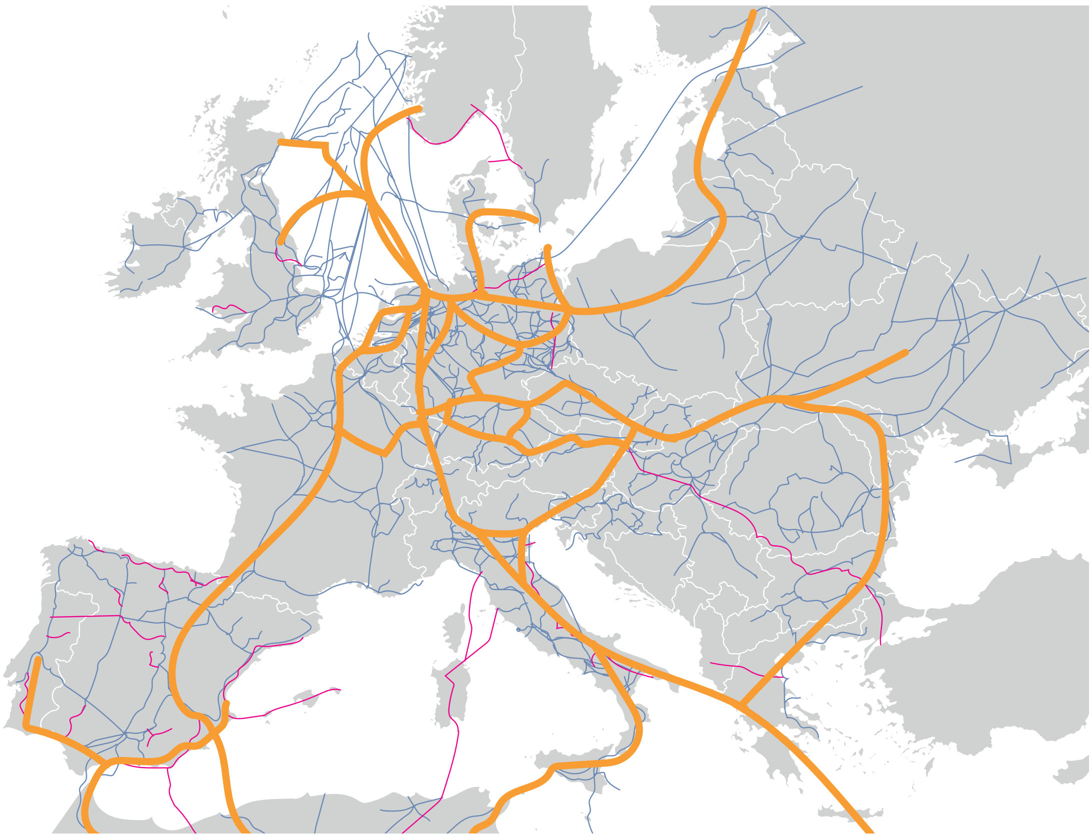


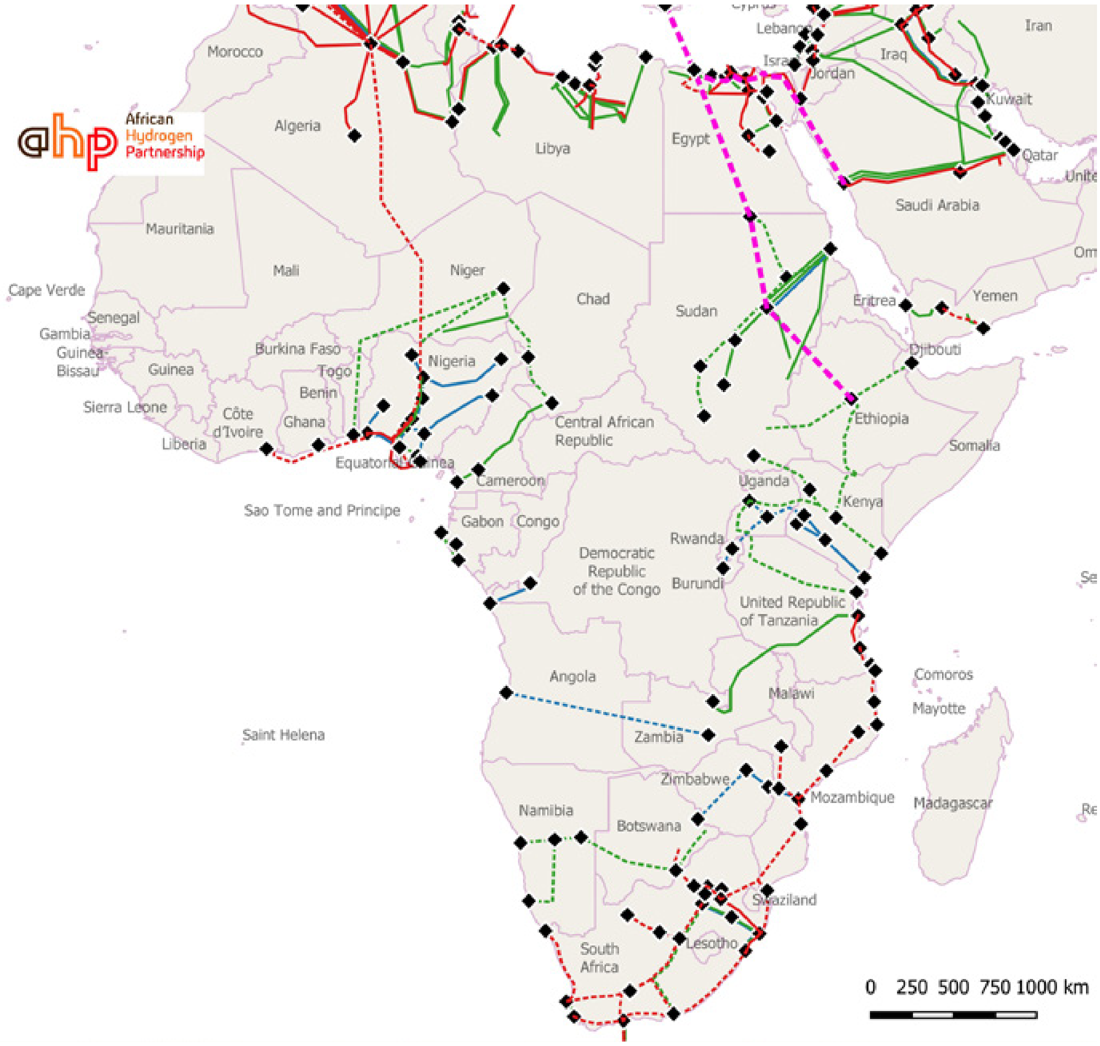
***Figure 7** European Transnational Hydrogen Backbone - The natural gas infrastructure in Europe (blue and red lines) and an outline for a hydrogen backbone infrastructure (orange lines). The main part of the hydrogen backbone infrastructure consists of re-used natural gas transport pipelines with new 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 realised.*

## Connecting Africa and Europe for green energy delivery

North Africa has even better and abundant solar resources than Europe, together with interesting wind resources. These solar and wind resources are more than sufficient to cover its own energy needs, in fact it could easily serve all the worlds energy needs. To date, North Africa is exporting natural gas from Algeria and Libya, with several pipeline connections to Spain and Italy. These pipeline connections have a capacity of more than 60 GW (Timmerberg & Kaltschmitt, 2019). In addition there are two electricity transport cables, each with a capacity of 0.7 GW, between Morocco and Spain. Morocco and Spain have signed in 2019 a Memorandum of Understanding to realize a third power interconnector of 0.7 GW (Tsagas, 2019), which will be used also to export solar electricity from Morocco to Spain. The capacity of these electricity inter-connections, however, is much less than the capacity of the gas interconnections. Therefore for Africa and Europe it would be very interesting to unlock the renewable energy export potential in North Africa, with North African countries converting this electricity to hydrogen and transport the energy via pipelines to Europe. Part of the natural gas grid could be converted to accommodate hydrogen (van Wijk A. , Wouters, Rachidi, & Ikken, 2019). But also, the construction of new hydrogen pipelines would be a cost-effective option, compared to construction of electricity cables, 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 about € 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 H2, which is a reasonable fraction of the total cost of delivered hydrogen (van Wijk & Wouters, 2019).

The African Hydrogen Partnership initiative, prepared an overview of existing and planned pipeline infrastructure for gas, oil and chemical products in Africa. They indicated what type of hydrogen product could be transported through these pipelines. The gas pipelines crossing the Mediterranean Sea could be potentially used to transport hydrogen gas too (Oldenbroek & Huegemann, 2019). In future, more hydrogen pipeline transport capacity is necessary. A dedicated new large pipeline infrastructure from Italy over Greece crossing the Mediterranean Sea to Egypt, eventually further extended to Ethiopia and the Middle East will be very instrumental to unlock the abundant and cheap renewable energy potential (van Wijk A. , Wouters, Rachidi, & Ikken, 2019). Figure 8 gives an overview of existing pipeline infrastructure and a new dedicated hydrogen pipeline between Africa and Europe.




**African Pipeline Infrastructure for future hydrogen transport**

- Hubs
- Hydrogen (Dedicated new pipeline)
- Gas Existing (Potential pure hydrogen use)
- Gas Future/Planned/Under Feasibility (Potential pure hydrogen use)
- Oil Existing (Potential LOHC/MCH[1] use)
- Oil Future/Planned/Under Feasibility (Potential LOHC/MCH[1] use)
- Chemical Products Existing (Potential ammonia/ LOHC/MCH[1] use)
- Chemical Products Future/Planned/Under Feasibility (Potential ammonia/ LOHC/MCH[1] use)

[1]LOHC; Liquid Organic Hydrogen Carrier, MCH; Methyl-Cyclo Hexane (hydrogen bound to toluene)

***Figure 8*** *Potential hydrogen infrastructure in Africa with connection to Europe – gas, oil and chemical transport pipelines, that can be potentially be used for hydrogen transport. There is a natural gas infrastructure between North-Africa and Europe that can be potentially used to transport hydrogen (Oldenbroek & Huegemann, 2019). A ''new'' dedicated hydrogen transport pipeline can be realized from Italy to Greece, crossing the Mediterranean Sea to Egypt, which could eventually be extended to Ethiopia and the Middle East (van Wijk A. , Wouters, Rachidi, & Ikken, 2019).and from Greece to the Black See, also along the South Coast of the Iberian Peninsula a dedicated hydrogen pipeline has to be realised.*

## 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) (van Wijk & Wouters, 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 dispatchable power plants, typically 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 or other products are stored, see figure 9.1 and 9.2. Salt caverns can be used to store hydrogen in the same way as they can store natural gas (HyUnder, 2013). Salt caverns to store hydrogen have been used for many decades, for example near Leeds in the UK.

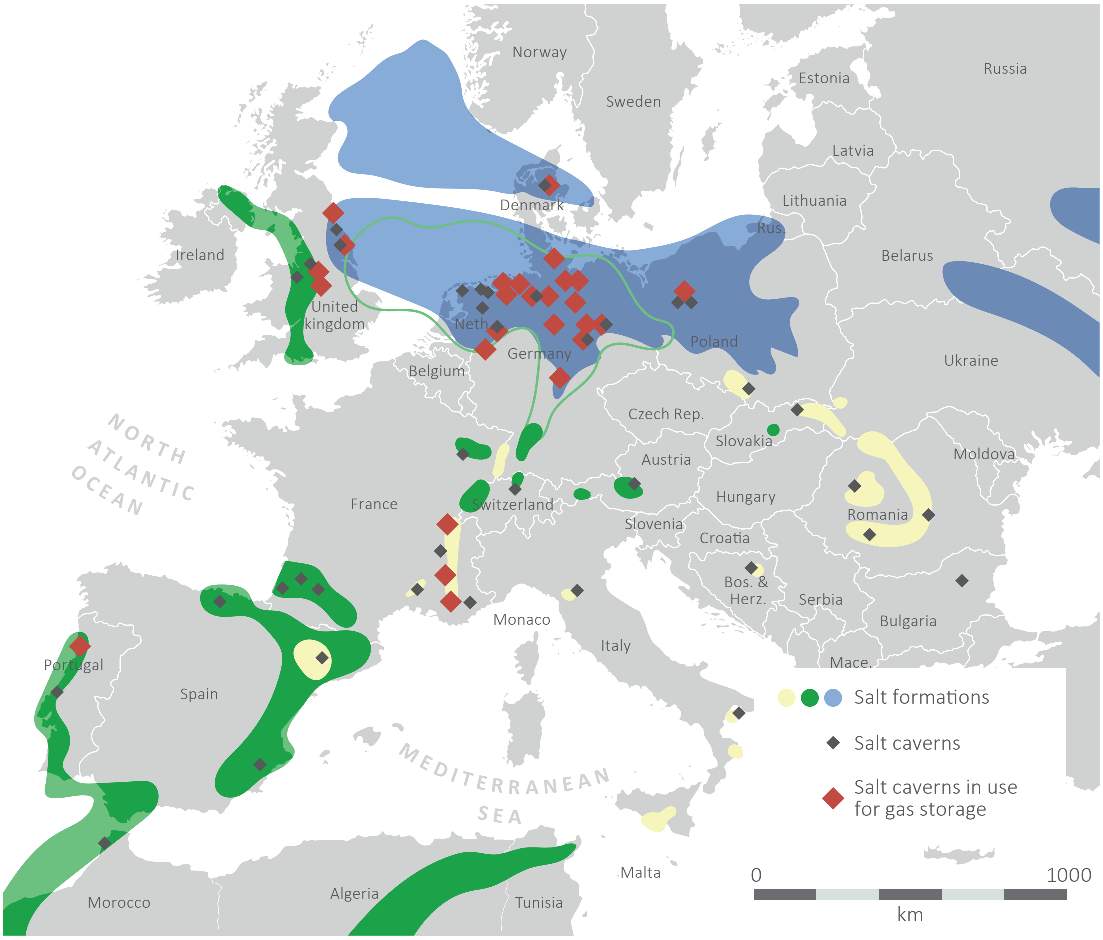



*Figure 9.1* *Salt formations with salt caverns throughout Europe. The red diamonds are salt caverns in use for natural gas storage (Bünger, Michalski, Crotogino, & Kruck, 2016)*

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 100 cheaper than battery storage.

Europe has many empty salt caverns available for large scale hydrogen storage. Besides new dedicated salt caverns for hydrogen, 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., 2020). And maybe hydrogen can be stored in some empty gas fields that meet specific requirements to store hydrogen.

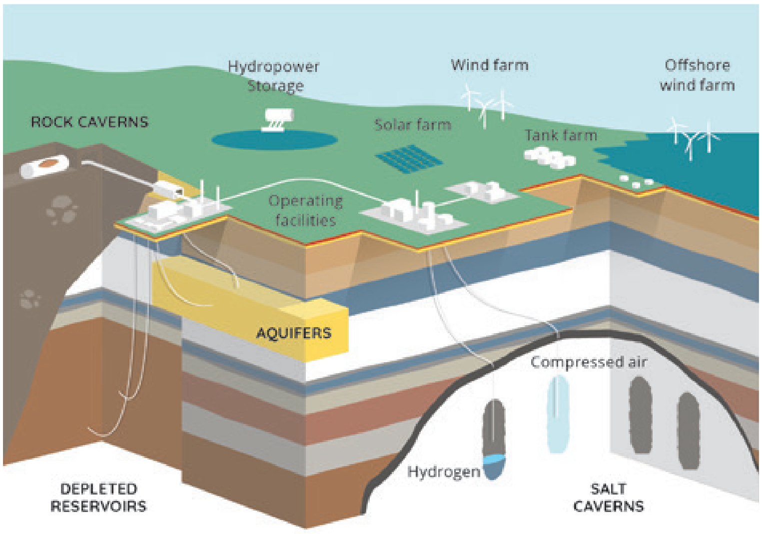



***Figure 9.2*** *Salt cavern (van Wijk, van der Roest, & Boere, 2017)*

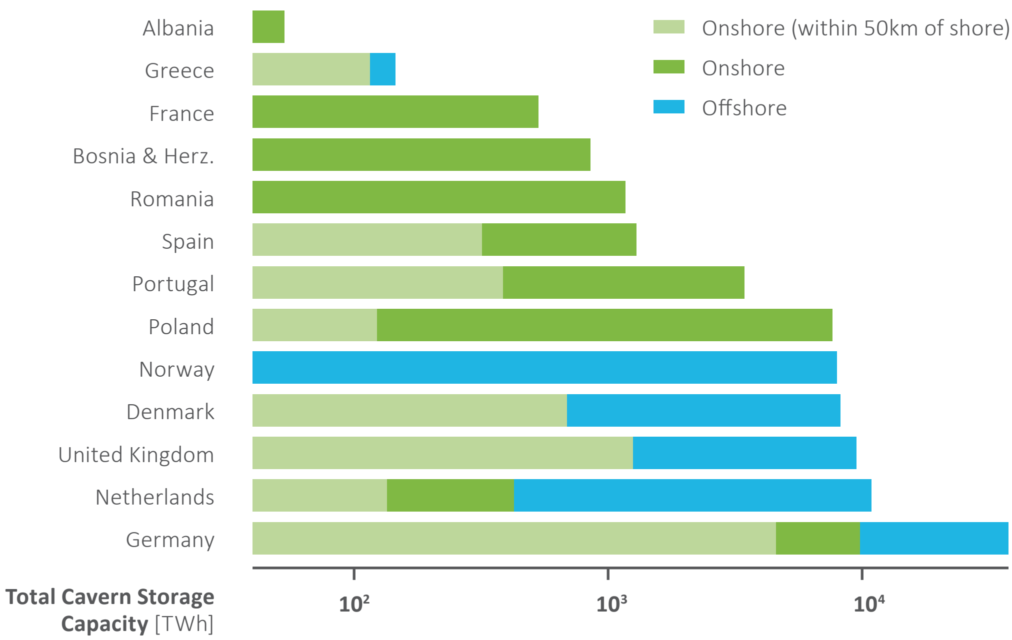



***Figure 10*** *Salt cavern hydrogen storage potential in Europe (Caglayan, et al., 2019)*

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

The difficult but crucial question is how to transition from a natural gas infrastructure to a hydrogen one in the next decade. Ramping up the hydrogen production capacity to fill a newly built or convert a natural gas pipeline into a hydrogen transport pipeline with a capacity of 15-20 GW takes time. Converting a natural gas transport pipeline into a hydrogen pipeline or building a new dedicated hydrogen pipeline is only fully 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.

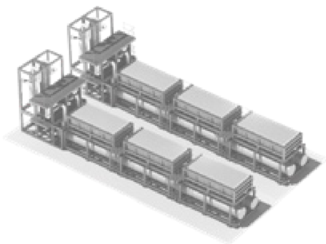
- In parallel to hydrogen produced through electrolysis, also stimulate the production of large quantities of carbon neutral hydrogen to have enough volume to fill a transport pipeline. This makes it possible to convert natural gas pipelines to hydrogen transport pipelines earlier.
- Blend hydrogen with natural gas. Some 2-5% of hydrogen could be blended in the natural gas transport grid without the need to replace or adjust compressors. Above 5%, the hydrogen could be blended in one specific transport pipeline, where the compressors are replaced or adjusted.
- 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, e.g. crossing the Mediterranean Sea or at the North Sea, without prohibitively high cost. At the same time, natural gas can still be transported, albeit with lower capacity.
- Build green Ammonia plants in harbour areas and export the hydrogen by shipping the ammonia. This ammonia, which is a combination of nitrogen and hydrogen, could be used in the fertilizer and chemical industry, it could be cracked back to hydrogen or it could directly be used as a fuel in maritime diesel engines or in converted power plants.
- Build hydrogen liquefaction plants in harbor areas and export liquid hydrogen in special cryogenic vessels similar to LNG. The liquid hydrogen can be easily re-gasified in the port of arrival and injected into a pipeline system. Or the liquid hydrogen could be sent to fueling stations in trucks carrying liquid hydrogen (up to 10 times more energy can be transported in liquid hydrogen than at pressurized hydrogen)
- Other solutions to ship hydrogen, such as Liquid Organic Hydrogen Carriers, combine hydrogen with $CO_2$ to produce methanol, formic acid, kerosene, or another synthetic hydrocarbon.

The preferred solution 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, due to the fact that Morocco is already working on large scale green ammonia production for the indigenous fertilizer production. 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 provide clever and cost-effective solutions.

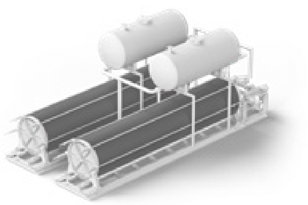
## Europe has a world class electrolyser industry for hydrogen production

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 green electricity, biogas, biomass or directly from sunlight. Hydrogen produced from biogas, biomass and 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.

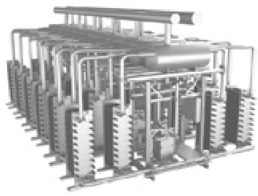
Although there is little dedicated hydrogen production via water electrolysis today, electrolysers are not a new technology. Today, worldwide about 20-25 GW of electrolyser capacity is operated mostly for chlorine production. By electrolysis of salt dissolved in water, chlorine is produced from the salt, 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 a strong world market position today. Especially the European industry delivers advanced high quality electrolysers which meet high safety standards. 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.



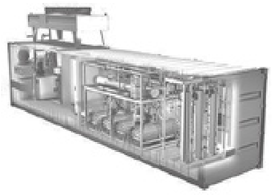
**Alkaline electrolyser ThyssenKrupp**



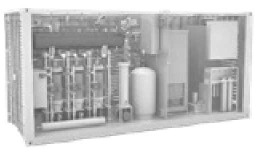
**Alkaline electrolyser NEL**



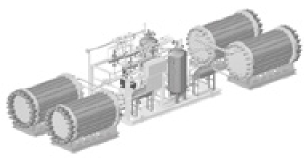
**PEM electrolyser Siemens**



**PEM electrolyser Hydrogenics**



**PEM electrolyser ITM Power**



**Alkaline electrolyser McPhy**

**SOEC electrolyser Sunfire**

***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 will contribute to a cleaner, decarbonised Europe, Africa and far beyond.

However, such a hydrogen economy requires a coordinated European approach in collaboration with Africa and their neighbouring regions (e.g. 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 close coordination with the development of the electricity market and electricity infrastructure as well as the gas infrastructure for hydrogen.

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 up to the year 2030.

> We, the European hydrogen 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 its neighbouring countries (e.g. 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 very 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 demonstration projects have been installed, but the time is now to scale up the electrolyser market in order to further bring down cost and to develop a strong and competitive European electrolyser industry through a massive scale roll out.

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 (e.g. kerosene) and to produce "green steel" from iron-ore in a reduction process using hydrogen instead of carbon monoxide. Next to these industrial feedstock applications, a hydrogen market for the transport sector, high and low temperature heat for industry and buildings 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).

**Captive market: Hydrogen production near the hydrogen demand**

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 several hundred MW's maximum.

In the near future, a hydrogen market for transport fuels will emerge. At hydrogen refuelling 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 in gaseous form by truck or pipeline or in liquid form using special cryogenic trucks. The 1-10 MW scale market for electrolysers at hydrogen refuelling stations will grow in the coming decade.

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, and will grow in the coming decade.

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. However, in many cases, the capacity limitations of the electricity grid and the electricity grid fees will provide a significant bottleneck for low cost hydrogen production.

**Hydrogen market: Hydrogen production at the energy resource**

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 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 it to all kinds of consumers: industry, mobility, houses, buildings and balancing power plants. Because these electrolysers are connected to renewable electricity production and not to an electricity grid, the electrolysers will not produce in baseload. Such a hydrogen production plant is therefore not connected to an electricity grid, 'off grid', whereby the load factor depends on the renewable electricity production by the solar and/or wind farm.

**Hydrogen market design**

The GW electrolyser market requires a European hydrogen market design, where the development of regulation needs to be an agile process and fit for purpose, that gives possibilities to gas infrastructure companies, Transmission System Operators (TSOs) and Distribution System Operators (DSOs) 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. The gas infrastructure companies, TSOs and DSOs, shall create an open access infrastructure to connect hydrogen producers and customers. Also, hydrogen storage facilities need to be developed and connected to this hydrogen infrastructure, guaranteeing supply to customers at all times, independent of (seasonal) variations of renewable electricity. An energy certification system, across borders needs to ensure integrity of the connected markets for renewable, low-carbon hydrogen. In such a cross-border organized energy market GW-scale electrolysers will be able to produce and trade certified hydrogen for an emerging hydrogen market.

A tight interaction between the electricity and hydrogen systems and markets will become pivotal. Once a hydrogen pipeline infrastructure will be in place, also electrolysers in the range of 10-100 MW could be installed near small and medium scale renewable electricity production locations. If the electricity grid capacity to connect solar or wind farms to the electricity grid is insufficient, 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. In a recent study conducted by ENTSO-E and ENTSO-G, the associations of European electricity and gas TSOs, between 300 and 800 TWh electricity needs to be fed to electrolysers by 2050 to stabilize the electricity system (Collins, 2020).

The market design of such a European hydrogen market interconnected with other regions, can be informed by the natural gas and electricity market designs, but needs to incorporate appropriate flexibility mechanisms enabling market players to switch converting electricity to hydrogen and vice-versa, with distinct roles for producers, infrastructure companies, TSOs and DSOs, independent regulators, cross boundary market mechanisms between countries and other regions and clear rules for grid access, pricing, clearing, gas quality, safety etc.

## Roadmap 40 GW electrolyser capacity in the European Union 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 (FCH JU, 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 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Captive Market [MW]** | | | | | | | | | | | | **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 [MW]** | | | | | | | | | | | | **34,000** |
| **Centralised GW scale (Hydrogen plants)** | | | 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=6,000 MW) and a hydrogen market (34 GW=34,000 MW).*

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.

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

North Africa has very favourable solar and wind resources, while Ukraine has fair wind, solar and good 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 ship or electricity by power cables, 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. Morocco e.g., who doesn't have fossil resources, currently imports 1 million ton of ammonia per year, costing more than $400 million (Trendeconomy, 2018). 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. 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 available for hydrogen export to the EU in 2030, representing 17% of the total EU hydrogen demand in 2030, as presented in the Hydrogen Roadmap Europe (FCH JU, 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 co-operation between the EU and North Africa/Ukraine, the European electrolyser industry could develop an important market, which is crucial to become and remain a leader in this emerging technology.

| Electrolyser Capacity | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total 2030 |
|---|---|---|---|---|---|---|---|---|---|
| **Domestic Market [MW]** | | | | | | | | | **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 refuelling stations** | | | | | 10 | 20 | 30 | 40 | 100 |
| **Export Market [MW]** | | | | | | | | | **32,500** |
| **Hydrogen North Africa (Hydrogen plants)** | | 500 | 1,000 | 2,000 | 3,000 | 4,000 | 6,000 | 8,000 | 24,500 |
| **Hydrogen Ukraine (Hydrogen plants)** | | | 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 includes 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.

## Renewable hydrogen becomes cost competitive

Alkaline electrolysers are considered a mature technology, currently used to produce chlorine. PEM and SOEC electrolysers are going through a steep learning curve. Alkaline, PEM and SOEC 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. These 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) (HydrogenCouncil, 2020).

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 in Europe between 1.5-2.0 €/kg (HydrogenCouncil, 2020).

In 2025, renewable hydrogen will become competitive with low-carbon hydrogen (1.5-2.0 €/kg) ór with grey hydrogen together with a 50 € per ton $CO_2$ price (HydrogenCouncil, 2020). (When hydrogen is produced from natural gas, every 10 € per ton $CO_2$ price adds about 0.1 €/kg to the hydrogen price.)

In 2030 renewable hydrogen is expected to become competitive with grey hydrogen, at 1.0-1.5€/kg.

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. Transport by ship is more expensive than pipeline transport. Hydrogen import from North Africa, however, will certainly become 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 to the Capex, Opex and efficiency developments for the electrolysis equipment as presented in table 3. The Capex and electricity cost are presented as a range. The low Capex and electricity cost will be realised at the 'off grid'' multi GW solar and wind hydrogen plants at good renewable energy resources sites. The high Capex and electricity cost will be realised at multi MW scale electrolyser connected to solar/wind farms and the electricity grid, located near the hydrogen demand. Although Capex and Opex cost reductions are important, the electricity cost reductions are the most important. (Every 10 €/MWh less electricity cost at 80% electrolyser efficiency HHV (Higher Heating Value), translates in a hydrogen cost reduction of 0.5 €/kg)

Hydrogen price 1€/kg equals

- 7€/GJ $H_2$
- 0.025€/kWh $H_2$
- 0,09€/$m^3$ $H_2$
- 0.24€/$m^3$ natural gas equivalent

| **Hydrogen production by electrolysers*** | **Capex (€/kW)** | **OPEX %/yr Capex** | **System Efficiency (HHV**)** | **Electricity (4.000-5.000hr) (€/MWh)** | **Hydrogen (€/kg)** |
|---|---|---|---|---|---|
| **2020-2025** | 300-600 | 1.5% | 75-80% | 25-50 | 1.5-3.0 |
| **2025-2030** | 250-500 | 1% | 80-82% | 15-30 | **1.0-2.0** |
| **Up to 2050** | <200 | <1% | >82% | 10-30 | 0.7-1.5 |

*Hydrogen production cost for hydrogen delivered at 30 bar pressure and 99,99% purity
**HHV = Higher Heating Value

***Table 3*** *Green hydrogen production cost development*

GW scale electrolysers at good wind and solar integrated electricity-hydrogen production sites can produce renewable hydrogen at costs competitive with low-carbon hydrogen (1.5-2.0€/kg) in 2025 and with grey hydrogen, (1.0-1.5€/kg) in 2030.

## Impact 2x40 GW green hydrogen production

Renewable hydrogen production will not emit greenhouse gases such as carbon dioxide ($CO_2$) and can decarbonise the energy use in hard to abate sectors such as industry and heavy transport sectors.

Above all, realizing 2x40 GW electrolyser capacity in 2030 can create a world class leading electrolyser industry in Europe. This industry will contribute to economic growth and jobs, not only in the European Union but also in North-Africa and Ukraine. And creating economic growth and jobs in North-Africa could possibly contribute to less immigration.

### $CO_2$ emission reduction

Hydrogen production from solar and wind does not contribute to $CO_2$ emissions to the atmosphere. It is assumed that green hydrogen replaces grey hydrogen produced from natural gas by steam methane reforming. The average greenhouse gas emission factor, expressed in $CO_2$ equivalent emission, for grey hydrogen according to the certification of hydrogen by CertifHy is 10.9 kg/kg $H_2$ (CertifHy, 2019).

Total avoided $CO_2$ emissions by 2x40 GW green hydrogen production is 90 MTon per year.

The European Union reduces $CO_2$ emissions with 82 MTon per year by green hydrogen production in the European Union and import from North-Africa/Ukraine

Total Hydrogen production by 2x40 GW is estimated to be 9.3 million ton $H_2$. The total avoided $CO_2$ emissions are therefore 90 million ton $CO_2$. However, part of the hydrogen produced in North Africa and the Ukraine is produced and used for own consumption and not exported to the EU. The avoided $CO_2$ emissions in the EU by the green hydrogen production in the EU and the import from North Africa and the Ukraine are about 82 million ton $CO_2$.

### Investments in 2x40 GW electrolyser capacity

Based on the roadmaps for electrolyser capacity development in Europe and North Africa/ Ukraine and the electrolyser Capex as depicted in table 3, the total electrolyser investments can be calculated. For captive hydrogen production near the hydrogen demand and decentralised hydrogen production the higher Capex figures are used to calculate these electrolyser investments. For multi GW integrated solar and wind hydrogen production plants the lower Capex figures are used to calculate these electrolyser investments. The total investments in 2 X 40 GW electrolyser capacity are calculated to be between €25 and €30 billion. According to the roadmaps, over 85% of all electrolyzer capacity will be realised in the 2025-2030 timeframe, which explains the relatively low total investment costs.

These electrolyser investment cost, does not include the investments in solar and wind farms. Also, the investment cost in infrastructure, pipelines, compressors, salt cavern storage and the necessary investments in hydrogen application equipment are not included in this figure. Especially the investment cost in the necessary and additional solar and wind capacity of about 100-150 GW will be substantially more than the investment cost in the electrolyser capacity. Depending on the share of solar, wind onshore and wind offshore, total investment cost could be very roughly estimated between €100 and €300 billion.

Total investment in 2x40 GW electrolyser capacity is between €25 and €30 billion

### Creating jobs

The number of jobs that can be created by manufacturing and maintenance of electrolysers is estimated in a study for the FCH JU (Fuel Cell Hydrogen Joint Undertaking) to be approximately 5.5 full time equivalent jobs (direct and indirect employment) per million Euro of electrolyser production value (FCH JU, September 2019). This is the amount of jobs created in the total electrolyser supply chain. If we assume that all the 2x40 GW electrolyser capacity will be manufactured and maintained in the EU, the number of jobs created in the EU will be between 140,000 and 170,000 full time jobs up to 2030. By developing a strong and competitive European electrolyser industry, jobs will be created up to 2030, but many more jobs will be created after 2030. Besides a manifold of jobs will be created by realizing the connected renewable energy capacity.

Number of jobs for manufacturing and maintenance of 2x40 GW electrolyser capacity is between 140,000 and 170,000 up to 2030

# WHAT WE OFFER AND WHAT WE NEED

We, the hydrogen 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.

## Green Hydrogen Initiative 2x40 GW in 2030

### What we offer

- Significant reduction in electrolyser costs
- Renewable hydrogen competitive with low-carbon hydrogen in 2025 and with grey hydrogen 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 realised 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, e.g. clean hydrogen quota for decarbonised gas
- 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 realised.

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

## References

BDEW. (2018). Monthly natural gas consumption in Germany. Retrieved from https://www.cleanenergywire.org/dossiers/role-gas-germanys-energy-transition

Bundesnetzagentur. (2019, May). Quartalsbericht zu Netz- und Systemsicherheitsmaßnahmen; Gesamtjahr und Viertes Quartal 2018. Retrieved from https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2019/Quartalsbericht_Q4_2018.pdf?__blob=publicationFile&v=4

Bünger, U., Michalski, J., Crotogino, F., & Kruck, O. (2016). Compendium of Hydrogen Energy. In Large Scale Underground Storage of Hydrogen for the Grid Integration of Renewable Energy and Other Applications (pp. 133-163). Sawston, UK: Woodhead Publishing.

Caglayan, D., Weber, N., Heinrichs, H., Linßen, J., Robinius, M., Kukla, P., & Stolten, D. (2020). Technical Potential of Salt Caverns for Hydrogen Storage in Europe. International Journal of Hydrogen Energy.

CertifHy. (2019, March). CertifHy-SD Hydrogen Criteria. Retrieved from https://www.certifhy.eu/images/media/files/CertifHy_2_deliverables/CertifHy_H2-criteria-definition_V1-1_2019-03-13_clean_endorsed.pdf

Collins, L. (2020, January 30). Retrieved from Recharge: https://www.rechargenews.com/transition/green-hydrogen-demand-in-europe-a-100gw-opportunity-for-renewables/2-1-747581

Dii, & FraunhoferISI. (2012, May 22). Desert Power 2050 Perspectives on a Sustainable Power System for EUMENA. Presented at SWP Berlin.

DNV-GL. (2017, November). Verkenning Waterstof Infrastructuur (in Dutch). Retrieved from Report nr. OGNL.151886,rev.2: https://topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/DNVGL%20rapport%20verkenning%20waterstofinfrastructuur_rev2.pdf

Energylivenews. (2019, August). Retrieved from https://www.energylivenews.com/2019/08/28/statkraft-and-baywa-team-up-for-second-subsidy-free-solar-plant-in-spain/

Entrance. (2017). Electricity and gas consumption in the Netherlands. Retrieved from https://www.ebn.nl/wp-content/uploads/2019/03/EBN_Infographic-2019_14MRT19.pdf

FCH JU. (2019). Hydrogen Roadmap Europe, a sustainable pathway for the european energy transition. Retrieved from https://fch.europa.eu

FCH JU. (September 2019). Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies; Evidence Report. Retrieved from https://www.fch.europa.eu/sites/default/files/Evidence%20Report%20v4.pdf

Gasunie. (2018, November). Retrieved from https://www.gasunie.nl/nieuws/waterstofleiding-gasunie-van-dow-naar-yara-in-gebruik-genomen

Gasunie. (2019). Retrieved from https://www.dewereldvanwaterstof.nl/gasunie/infrastructuur/

Guardian, T. (2019, September). New windfarms will not cost billpayers after subsidies hit record low. Retrieved from https://www.theguardian.com/environment/2019/sep/20/new-windfarms-taxpayers-subsidies-record-low

HydrogenCouncil. (2017, November). Hydrogen scaling up; a sustainable pathway to the global energy transition. Retrieved from http://hydrogencouncil.com/study-hydrogen-scaling-up/

HydrogenCouncil. (2020, January). Path to Hydrogen Competitiveness; A cost perspective. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

HyUnder. (2013). Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe . EU report 14-8-2013 www.fch.europa.eu.

IEA. (2019). The Future of Hydrogen, seizing today's opportunities. Report prepared by the IEA for the G20 Japan .

Kiwa. (2018). Toekomstbestendige gasdistributienetten (in Dutch). Rapport for Netbeheer Nederland.

Michalski, J., Bünger, U., Crotogino, F., Donadei, S., Schneider, G., Pregger, T., & al, e. (2017). Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition. International Journal of Hydrogen.

Northern Netherlands Innovation Board, p. a. (2017). The Green Hydrogen Economy in the Northern Netherlands, full report. Retrieved from http://verslag.noordelijkeinnovationboard.nl/uploads/bestanden/dbf7757e-cabc-5dd6-9e97-16165b653dad/3008272975/NIB-Hydrogen-Full_report.pdf

Oldenbroek, V., & Huegemann, S. (2019, March). Retrieved from African Hydrogen Partnership initiative: https://www.afr-h2-p.com/post/hydrogen-trade-potential-in-african-pipeline-infrastructure

Stratmann, K. (2020, January 28). energiewende-gasnetzbetreiber-legen-plan-fuer-deutschland-weites-wasserstoffnetz-vor. Retrieved from Handelsblatt: https://www.handelsblatt.com/politik/deutschland/energiewende-gasnetzbetreiber-legen-plan-fuer-deutschlandweites-wasserstoffnetz-vor/25476674.html

Timmerberg, S., & Kaltschmitt, M. (2019). Hydrogen from renewables: Supply from North Africa to Central Europe as blend in existing pipelines - Potentials and costs. Applied Energy 237, 795-809.

Trendeconomy. (2018). Retrieved from https://trendeconomy.com/data/commodity_h2/281410

Tsagas, I. (2019, February 20). Retrieved from PV Magazine: https://www.pv-magazine.com/2019/02/20/spains-third-interconnection-with-morocco-could-be-europes-chance-for-african-pv-or-a-boost-for-coal/

UkrainianHydrogenCouncil. (2019). Retrieved from Atlas of energy potential of renewable energy sources in Ukraine: https://hydrogeneurope.eu/member/ukrainian-hydrogen-council

van Son, P., & Isenburg, T. (2019). Emission free energy from the desserts. The Hague: Smart Book Publishers.

van Wijk, A., & Wouters, F. (2019, September). 'Hydrogen, the Bridge between Africa and Europe'. Retrieved from To be published in: Shaping an Inclusive Energy Transition, Springer, 2020: http://profadvanwijk.com/wp-content/uploads/2019/09/Hydrogen-the-bridge-between-Africa-and-Europe-5-9-2019.pdf van Wijk, A., van der Roest, E., & Boere, J. (2017). Solar Power to the People. Nieuwegein-Utrecht: Allied Waters.

van Wijk, A., Wouters, F., Rachidi, S., & Ikken, B. (2019, November). A North Africa - Europe Hydrogen Manifesto. Retrieved from https://dii-desertenergy.org/wp-content/uploads/2019/12/Dii-hydrogen-study-November-2019.pdf

Varadi, Wouters, & Hoffmann. (2018). The Sun is Rising in Africa and the Middle East - On the Road to a Solar Energy Future. Singapore: Pan Stanford Publishing Co ISBN-10: 9814774898 .

Vattenfall. (2018, March). Nuon wins permit for Dutch offshore wind farm without subsidy. Retrieved from https://www.government.nl/latest/news/2018/03/19/nuon-wins-permit-for-dutch-offshore-wind-farm-without-subsidy

Vattenfall. (2019, July). Retrieved from https://english.rvo.nl/news/vattenfall-build-second-unsub-sidised-dutch-offshore-wind-farm

Vermeulen, U. (2017). Turning a hydrogen economy into reality. presentation at 28th meeting Steering committee IPHE, the Hague.

# Colophon

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**Publisher** Hydrogen Europe

**Printed by** Paperland, Belgium

**Layout** Paul Grabowski

**Photo credits**
page 8: Zbynek Burival, unsplash
page 13: Dr. Thomas Isenburg
page 14: Nicholas Doherty, unsplash
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**ISBN** ISBN: 978-90-827637-1-3


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Brussels, March 2020

This publication is initiated by 'Hydrogen Europe' and endorsed by 'African Hydrogen Partnership Initiative', 'Ukrainian Hydrogen Council', 'Dii Desert Energy' and 'EU-GCC Clean Energy Technology Network'. The authors acknowledge especially the valuable comments and review by the FCH JU from Nikolaos Lymperopoulos.



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Appendix

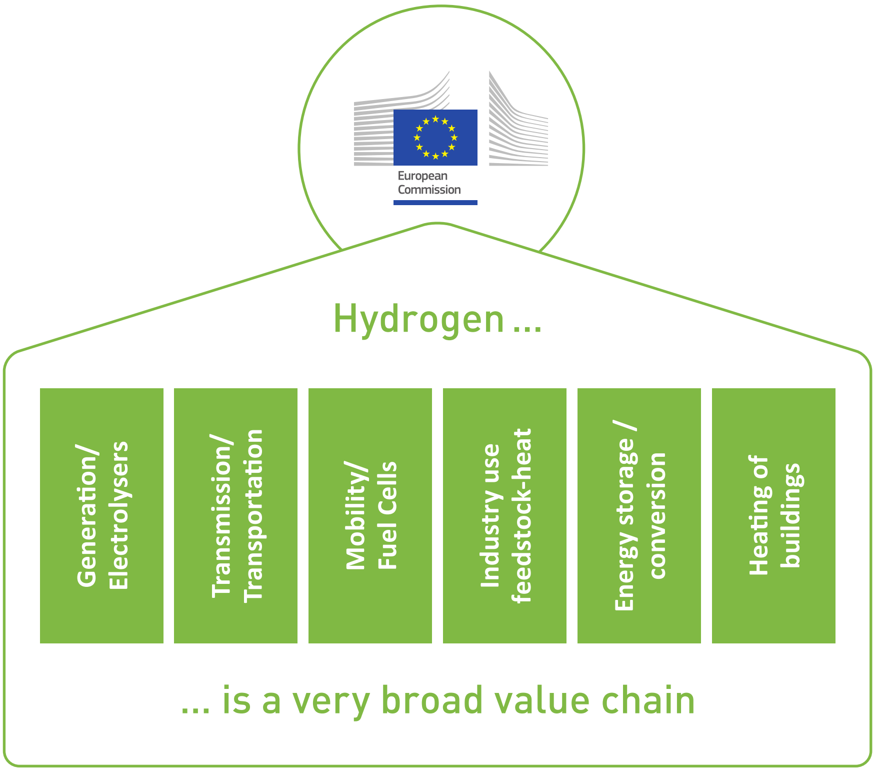
# HYDROGEN FOR CLIMATE ACTION

## IPCEI (Important Project of Common European Interest) on Hydrogen www.hydrogen4climateaction.eu

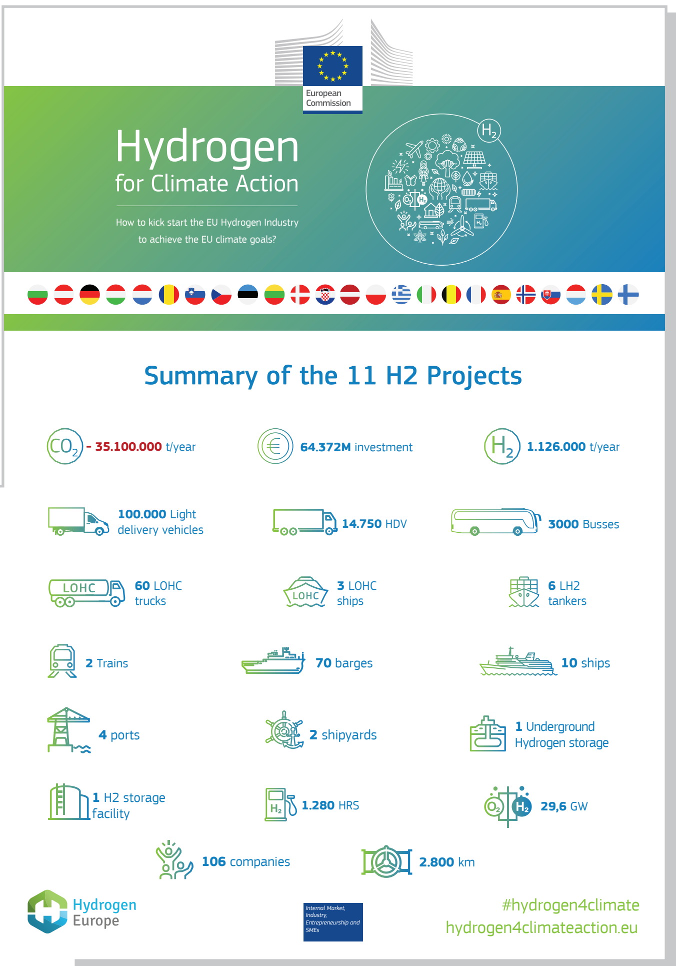
Hydrogen has been selected by the European Commission as a strategic value chain and is therefore undergoing a process of managing one or several IPCEI's on hydrogen. The link between the existing gas infrastructure and the TEN-T corridors for mobility would create an excellent basis to develop hydrogen 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, $NH_3$, 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

## Disclaimer

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English 03/2020

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