The crucial role of low-carbon hydrogen production to achieve Europe’s climate ambition: A technical assessment

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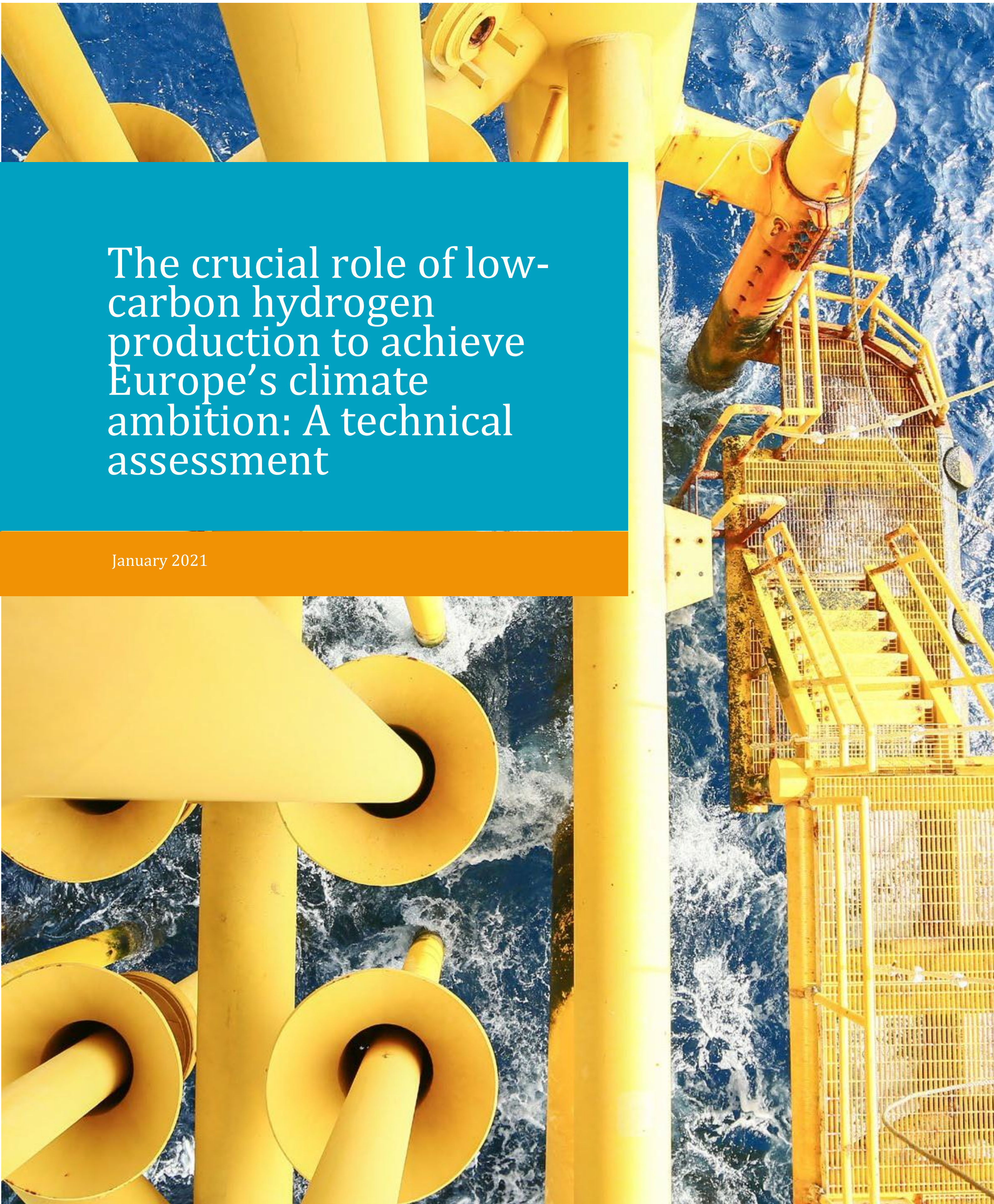

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Executive Summary

Hydrogen has emerged as a central narrative of the European Green Deal. With the legally-binding objective of climate neutrality by 2050, set by the European Climate Law and the increased climate target for 2030, the need to speed up the efforts towards climate change mitigation is evident. The EU is therefore relying on hydrogen as a way to decarbonise energy-intensive industries, energy and transport sectors.

The EU hydrogen strategy, published in July 2020, highlights that both renewable and low-carbon hydrogen with carbon capture and storage (CCS) are included in the strategy, although in the long-term perspective the European commission foresees a focus on production of renewable hydrogen.

It remains clear that low-carbon hydrogen produced from reformed natural gas with CCS will play a key role in paving the way towards a clean hydrogen economy for Europe, as the only opportunity to deliver early, large-scale quantities of hydrogen to industries and thus kickstarting a cost-efficient decarbonisation.

With many initiatives announced at EU and national level in support of hydrogen, and an ever-increasing evidence base to support hydrogen deployment across the hydrogen value chain, this report argues for a technology neutral approach to hydrogen production and presents an overview of the role of low-carbon hydrogen production alongside renewable hydrogen, in terms of production methods, costs, scalability and timelines to operation.

Some of the key conclusions of the report are:

- **Both renewable hydrogen and low-carbon hydrogen from reformation of methane with CCS have important roles to play in an EU hydrogen economy**.
    - Low-carbon hydrogen production from Steam Methane Reformers (SMR) is well understood, and production from both Auto-Thermal Reformers (ATR) and Partial Oxidation (POX) are in the states of early to medium commercial deployment. Reformers with CCS also offer future carbon removal potential using biomethane to create 'biohydrogen'.
    - Hydrogen production from electrolysis is also well understood, but as yet does not produce hydrogen at an industrial scale. Technologies such as Polymer Electrolyte Membranes (PEM) and Solid Oxide Electrolysis Cells (SOEC) have made the electrolysis process more cost effective and are in the late stages of development and looking to move into commercial scale deployment.

- **The development of shared CO_2 infrastructure networks between hydrogen producing industrial regions underpins the future of an effective EU hydrogen economy**.
    - Without which, renewable hydrogen will struggle to reliably produce hydrogen volumes required to enable at scale deployment of end-use sectors such as

industry, transport, heating and power generation.

  - Early volumes of low-carbon hydrogen can create a hydrogen market and infrastructure backbone which can 'pave the way' for renewable hydrogen over time.

- **By fulfilling early hydrogen demand, low-carbon hydrogen will give more time to plan and build the infrastructure required to scale up renewable hydrogen.**
  - The electrification of many sectors and introduction of green hydrogen production will drastically increase demand on the electricity infrastructure and generation capacity. New electricity generation capacity will need to be built to accommodate this demand and give resilience to a 'peakier' energy system. To build new facilities and upgrade the electricity network will require planning, which could take several decades. Low-carbon hydrogen can be deployed relatively quickly and utilise current energy infrastructure – ensuring network planning and generation capacity construction can occur in the most cost effective and joined-up way nationally and between member states.

- **The repurposing of existing natural gas infrastructure will be a key enabler for a hydrogen economy.**
  - Importantly, low-carbon hydrogen is critical to bridge the gap and prevent stranded assets, as low-carbon hydrogen can utilise the infrastructure networks as renewable hydrogen capacity expands. Without which, assets would become stranded, or maintained without any use, resulting in higher energy system costs.
- **Low-carbon hydrogen production with CCS (including upstream emissions) will have a lower carbon footprint than electrolysis using electricity until electrolysis can supply hydrogen below at least 22.4-46gCO_2/MJ**.
  - Hydrogen production from electrolysis only has a lower carbon footprint than low-carbon hydrogen in a handful of locations.

- **Hydrogen storage is a critical component of a hydrogen energy system**.
  - It is key to ensure resilience for small early networks with industrial processes (i.e. to allow for maintenance outages). Likewise, for mature, larger networks (from the 2040s), storage is essential to balance peaking production from a largely renewable based hydrogen system.

- **Without low-carbon hydrogen, 2030 hydrogen ambitions will not be met.**
  - For example, Germany has hydrogen ambition of 90-110TWh demand in 2030, with only 14TWh of domestic renewable hydrogen production resulting in a 76-96TWh gap. Low-carbon hydrogen can be deployed at scale, in the 2020s with a land-use footprint over 100 times smaller than an equivalent renewable hydrogen production.

- **Projects are preparing to deploy in the 2020s using hydrogen in hard-to-abate sectors such as producing hydrogen from the off-gases from the petrochemical process.**
  - For example, the H-vision project in Rotterdam uses off-gases from the local industry with CCS and has several additional up-sides in the national energy transition perspective compared to alternatives.
    1) It creates a direct additional reduction of carbon dioxide emissions without laying an extra claim on renewable capacity from wind and solar.

2) It supports further decarbonisation options such as electrification.
3) It is a kick-starter for a more feasible low carbon hydrogen infrastructure. The installed reforming plants for the purpose of H-vision can also be used in the future to decarbonise other hydrocarbons and even biogas.

Recommendations for policymakers

- Propose a consistent EU-wide hydrogen terminology and subsequent classification and thresholds based on life-cycle greenhouse gas (GHG) emissions savings.
- Under the EU Taxonomy, it is not exactly clear how the current threshold of 2.256 tCO_2eq/t has been designed and whether it will decline over time. Power Purchase Agreements – with both temporal and geographical correlation - should be introduced to comply with the electricity threshold.
- Ensure the Trans-European Networks for Energy (TEN-E) and EU Emissions Trading System (ETS) can include all CO_2 transport modalities for European CO_2 infrastructure, connecting emitters with storage sites.
- CO_2 and hydrogen storage should also be included in the TEN-E Regulation as storage is an essential part of the CO_2 and hydrogen infrastructure component of a CCS project. CO_2 and hydrogen storage is a key element to delivering real climate change mitigation and it should be eligible to receive funding as part of the Connecting Europe Facility for Energy (CEF-E).
- Repurposing and retrofitting of natural gas infrastructure for the transport of CO_2 and low-carbon gases (such as hydrogen) should be included in revised TEN-E guidelines.
- Hydrogen infrastructure planning should be integrated in the TEN-E and Ten-Year Network Development Plan (TYNDP) frameworks. In particular, attention should be given to possible synergies between hydrogen and CO_2 infrastructure to achieve low-carbon hydrogen production at large scale while tackling hard-to-abate emissions (e.g. in port areas and industrial clusters).
- Relevant Next Generation EU and Multiannual Financial Framework (MFF) funding instruments (such as the Recovery and Resilience Facility, cohesion funding, Horizon Europe, Connecting Europe Facility, InvestEU and the Just Transition Mechanism) can further accelerate hydrogen deployment and should consistently support both renewable and low-carbon options.
- The forthcoming European Partnership for Clean Hydrogen, building on the success of the existing FCH 2 JU, should be broadened to include all end-use sectors, all renewable and low-carbon hydrogen production technologies as well as innovation in business models, processes and market creation in its scope.
- Make R&I funding available for all low-carbon hydrogen production technologies and clearly communicate the opportunity to industry.
- Ensure the revision of the State Aid Guidelines for Environmental Protection and Energy (EEAG) covers wider CCUS and hydrogen activities in addition to those already represented. Including CO2 transport via modalities other than pipelines and retrofit pipelines for CO2. To enable the development of hydrogen networks, the deployment of low-carbon hydrogen infrastructure and retrofit activities should also be to qualify for state aid should also be able to qualify for state aid under the EEAG.

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1. Introduction

On 11 December 2019, the European Commission (EC) presented the European Green Deal – the growth strategy for making the EU's economy sustainable – highlighting the main policy initiatives for reaching net-zero greenhouse gas (GHG) emissions by 2050, while ensuring economic growth and a just transition.

The EUs climate ambition for 2030 and 2050 is the fundamental objective of the European Green Deal. Hydrogen is key for reducing emissions and is central to the EU strategy for integrated energy systems given its cross-sector application. This is because hydrogen can ensure deployment of decarbonisation technologies and provide a stable and flexible energy system, while meeting the needs and demands of the electricity, heat, transport and industrial sectors. The importance of both hydrogen and CCS is confirmed by the impact assessment accompanying the 2030 Climate Target Plan, which shows that a decarbonised energy system will require going beyond electrification and that further deployment of both renewable and low-carbon fuels will be needed in order to meet increased climate ambitions. Slow progress on energy system integration and on the uptake of low-carbon technologies such as CCS will affect the pathway to climate neutrality negatively – especially if combined with a lack of dedicated infrastructure and markets.[1]

The EU's energy system today relies on natural gas, oil and electricity (which is just short of 50% fossil-based). Hydrogen is well suited to be a key low-carbon energy carrier, utilising the energy system hydrogen from both natural gas with carbon capture and storage (CCS) and renewable electricity via electrolysis, resulting in a mix of production technologies, resilience and security for the energy system. It is in this perspective that nearly all EU member states plan for hydrogen in their National Energy and Climate Plans (NECPs), with several outlining a plan for hydrogen from natural gas with CCS and carbon capture and utilisation (CCU).[2] Technology-neutrality on EU level is crucial to successfully support the member states' national hydrogen strategies which vary in their approaches to hydrogen production and scale-up. This is also clearly highlighted in the European Taxonomy for Sustainable Finance (Taxonomy), where manufacturing of both electrolysis- and CCS-based hydrogen are defined as sustainable economic activities, given certain screening criteria.

For many energy-intensive industries (EII), decarbonisation through electrification is not possible nor realistic from either a cost or a technological point of view. Hydrogen provides one of few options for many industries to decarbonise, particularly those reliant on high temperature operations such as steel production. Fuel-switching to hydrogen should be an important part of the forthcoming EU Industrial Strategy. In order to scale up production and demand for renewable and

[1] SWD(2020) 176 final: Impact assessment accompanying the 2030 Climate Target Plan (p.12).
[2] See IOGP (2020): Assessment of National Energy and Climate Plans.

low-carbon hydrogen, coordinate action and provide a broad forum to engage, the EC has launched the European Clean Hydrogen Alliance, comprising investors, member states and a community of industry and research organisations.

1.1. Hydrogen terminology

The EU Hydrogen Strategy attempts to define hydrogen types based on production method, moving away from the commonly used "colours" of hydrogen (Box 1). However, the terminology proposed by the EU Hydrogen Strategy has created additional confusion.

More consistent, common terminology and a subsequent certification system will be needed when defining the scope of supportive policies and the eligibility of projects and products in future EU hydrogen support schemes. In this context, we recommend that the EC makes a legislative proposal for the establishment of such a common, EU-wide terminology based on life-cycle GHG emission savings which consistently covers *both* renewable and low-carbon hydrogen. Based on life-cycle GHG emission savings, the certification of hydrogen according to categories (e.g. "renewable", "low-carbon") could be an option for providing clarity to consumers.

Before the EU Hydrogen Strategy was published, it was commonly understood that the term "clean" hydrogen refers to *both* renewable and low-carbon hydrogen, including hydrogen from natural gas with CCS.)[3, 4] While the EU Hydrogen Strategy Communication is not a legally binding document, it is now unclear whether policymakers when using the term "clean" intend to refer to both renewable and low-carbon hydrogen or renewable hydrogen only. One example of the confused nomenclature is the European Clean Hydrogen Alliance, which refers to "clean" (i.e. renewable) hydrogen in its title, yet the Alliance is clearly intended to include

Box 1: Hydrogen definitions in the EU Hydrogen Strategy

Electricity-based hydrogen:

Hydrogen is produced through the electrolysis of water in an electrolyser, that is powered by electricity regardless of the electricity source. The full life-cycle greenhouse gas emissions of the production of electricity-based hydrogen depends on how the electricity is produced using fossil and renewable sources.

Renewable hydrogen:

Hydrogen is produced through the electrolysis of water in an electrolyser, powered by electricity, and with the electricity stemming from renewable sources. The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero. Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.

Clean hydrogen:

Reference is made to renewable hydrogen.

Fossil-based hydrogen:

Hydrogen is produced through a variety of processes using fossil fuels as feedstock, mainly the reforming of natural gas or the gasification of coal. This represents the bulk of hydrogen produced today.

Fossil-based hydrogen with carbon capture:

Hydrogen produced is fossil-based hydrogen, but greenhouse gases emitted as part of the hydrogen production process are captured.

Low-carbon hydrogen:

Reference is made to fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production.

[3] See IEA (2019): The Future of Hydrogen: *"**Clean hydrogen** technologies are available but costs remain challenging. Policies that create sustainable markets for **clean hydrogen**, especially to reduce emissions from fossil fuel-based hydrogen, are needed to underpin investments by suppliers, distributors and users. By scaling up supply chains, these investments can drive cost reductions, whether from low-carbon electricity or fossil fuels with carbon capture, utilisation and storage."*

[4] See also the EC-initiated Mission Innovation (2018) Innovation Challenge on Renewable and Clean Hydrogen, which includes a mission to *"improve CCUS technologies for **clean hydrogen**".*

both renewable and low-carbon hydrogen as evidenced by its scope and objectives.

1.2. Hydrogen in the European energy system

Solar and wind power, biomass, hydropower and geothermal energy are primary renewable energy sources in Europe. Integrating the energy supply produced from these sources into the current energy infrastructure presents challenges:

- The intermittent nature of solar and wind energy requires storage and flexible low-carbon electricity generation capacity to ensure security of supply.
- With the growing shares of intermittent electricity production, conditions of oversupply can increasingly occur once the installed capacity of intermittent supply exceeds the level of minimum hourly demand. Innovative flexibility options are required to absorb the growing amount of solar and wind energy.
- The location of renewable energy production and where it will be used requires, in most cases, transportation of renewable energy over long distances. Additionally, if extensive electrification would be possible, a significant increase in the existing electricity infrastructure would be necessary.
- Solar and wind energy technologies mainly produce electricity, the total amount of renewable energy currently constitutes about 18.9%[5] of the primary energy demand. As such, the growing electricity-based renewable energy sources are presently a lesser part of the energy system. Most likely, a considerable part of the energy system will have to rely on the use of molecules-based fuels (energy carriers).

The abovementioned challenges present a strong case for hydrogen, which is a versatile energy vector that can be used across all sectors: EII, transport, electricity production, and buildings, and it can also play an important role for zero-carbon domestic heating.

Hydrogen can provide flexibility for the energy system as a whole. In the shorter term, hydrogen produced from natural gas and combined with CCS can already be applied on a large scale as part of the energy supply for high-temperature heating in the chemical industry, oil-refining industry and electricity production. In the longer term, hydrogen can also be produced based on renewable electricity via electrolysis, and subsequently join the hydrogen market created by the frontrunner projects based on natural gas with CCS.

There is no "one size fits all" solution for hydrogen production technologies, as preferred production methods will vary depending on geography, geology and local energy systems. However, it must be noted that for most Member States, access to renewable electricity for electrolysis hydrogen production is limited and will likely remain so for the foreseeable future[6].

The EU Hydrogen Strategy acknowledged that hydrogen can be produced from different energy sources, including from fossil fuels with carbon capture and using renewable electricity. These production pathways have a broad impact on the mitigation of GHG emissions and relative competitiveness. As such, these production pathways are depending on the status of the technology, scalability, the energy source used, and have different cost implications and material requirements.

1.3. The role of hydrogen storage

An essential part of any hydrogen market is the storage of hydrogen, especially if the hydrogen is produced from fluctuating renewable energies. The most cost-efficient pathway is to use existing

[5] Eurostat : https://ec.europa.eu/eurostat
[6] Zero Emissions Platform (ZEP), 2017. Commercial Scale Feasibility of Clean Hydrogen Available at: http://www.zeroemissionsplatform.eu/component/downloads/downloads/1638.html

underground caverns which are currently operating with natural gas, or formerly with city gas. Gas storage in Europe has been done for many decades as such, countries such as Germany, the UK and the Netherlands have access to vast and long-term experience.

Importantly, hydrogen storage will play an evolving role as the hydrogen network and production methods develop over time:

- Early hydrogen networks will often centre around one or two hydrogen production facilities with a handful of local industrial users in local 'clusters'. Hydrogen storage in small networks is key to ensure a proportion of industrial demand can be met if the hydrogen production or end-user is unavailable or operating at reduced output (e.g. for maintenance).
- Mature hydrogen networks will be larger, connecting regions and industrial clusters through extensive infrastructure. Hydrogen production will be a mixture of renewable and low-carbon hydrogen. Hydrogen storage in this system will be critical to ensure renewable hydrogen can be stored for use in times of high demand. For example, a windy summer day will have low hydrogen demand, but high hydrogen production; hydrogen can then be stored for use on high demand days such as windless winter days.

Hydrogen storage is currently an active area of research and innovation. Today, many options exist for storing hydrogen in small volumes at the surface (e.g. pressurised vessels, liquid hydrogen tanks etc), however fewer options exist for hydrogen storage at industrial scale. Underground storage offers a solution for at scale hydrogen storage, salt caverns are used today for gas, air and hydrogen storage, and there is active research into using depleted gas fields, saline aquifers and rock caverns for underground storage. As with natural gas pipelines, surface infrastructure such as LNG terminals are also being investigated for potential repurposing for hydrogen.

The underground storage potential of hydrogen onshore as well as offshore in Europe is estimated up to a capacity of 84,800 TWh[7], thereof 27% is onshore sites only. Most of those storage sites are located in Germany, as it is considered to provide the largest share, followed by the Netherlands, UK, Norway, Denmark, Poland, France, Spain, Romania and Portugal.

Underground storage in salt caverns, rock caverns or depleted fields first needs to be analysed in terms of geological and technical criteria including the total volume of the cavern or reservoir; how fast hydrogen can be stored (i.e. charging of cavern/reservoir); how fast hydrogen can be discharged; how the underground composition might interact with hydrogen; and how impermeable the rock formation is to avoid hydrogen leakage.

Safety wise, gas storage is well understood, and any project will have to satisfy strict safety screening which analyse geological risks and potential, although extremely unlikely, hydrogen leaks. As an example, the project H2-UGS, part of the German initiative HYPOS, has been dealing with those issues as well as the study results from the German Research Centre Jülich (FZJ)[8] published in 2019/2020.

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[7] Caglayan D.G., Weber, N. et al. (2020), Technical potential of salt caverns for hydrogen storage in Europe, Int. J. Hydrogen Energy 45 (2020) 11, pp. 6793 or as pre-print (2019), internet download 9 Oct 2020

[8] Caglayan D.G., Weber, N. et al. (2020), Technical potential of salt caverns for hydrogen storage in Europe, Int. J. Hydrogen Energy 45 (2020) 11, pp. 6793 or as pre-print (2019), internet download 9 Oct 2020

2. Technologies for hydrogen production

Chapter 2: Key Messages

Low-carbon hydrogen can be produced through two main methods:

1) Methane reformation with CCS is a well understood industrial process done today using Steam Methane Reforming (SMR).
   - Newer technologies such as Auto Thermal Reformation (ATR) and Partial Oxidation (POX) with CCS offer increases efficiency and CO_2 capture rates >95%.
   - An active R&D focus on hydrogen production with CCS can increase capture and process efficiency and reduce both capital and operating costs.

2) Electrolysis is a well-founded technology which has traditionally been done on a small/pilot scale using alkaline solutions.
   - Newer technologies such as Polymer Electrolyte Membrane (PEM) and Solid Oxide Electrolysis Cells (SOEC) use the same principles in more efficient systems, this is in earlier stages of commercial deployment.
   - Advancing electrolysis technologies is an active area of R&D with the goal of increasing efficiency, reducing very high capital and operating costs and gaining practical operating experience.

There are different hydrogen production technologies, as mentioned in the section above. For more details on the hydrogen production technology, reference is made to the TNO database with up-to-date factsheets[9]. The two main streams of hydrogen production are electricity-based electrolysis of water and fossil-based reformation with carbon capture.

[9] https://energy.nl/en/search/?fwp_categories_en=hydrogen&fwp_content_type=factsheets

2.1. Hydrogen reformation

The principle of hydrogen reformation from natural gas is based on the reactions outlined in Box 2.

Box 2: Key hydrogen reformation reactions:

Reaction:	Δ H (KJ/mol)	
$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$	206	(1)
$CH_4 + CO_2 \leftrightarrow 2\ CO + 2\ H_2$	247	(2)
$CH_4 \leftrightarrow C + 2\ H_2$	75	(3)
$CO + H_2O \leftrightarrow CO_2 + H_2$	-41	(4)
$2\ CO \leftrightarrow C + CO_2$	-173	(5)
$CH_4 + \frac{1}{2}\ O_2 \leftrightarrow CO + 2\ H_2$	-36	(6)
$CH_4 + 2\ O_2 \leftrightarrow CO_2 + 2\ H_2O$	-803	(7)
$CO + \frac{1}{2}\ O_2 \leftrightarrow CO_2$	-284	(8)
$H_2 + \frac{1}{2}\ O_2 \leftrightarrow H_2O$	-242	(9)

Three technologies dominate the current production of hydrogen from methane, namely steam methane reforming (SMR), autothermal reforming (ATR), and partial oxidation (POX). Methane reforming by steam is mainly governed by the reforming reaction (1, 2) and water gas shift reaction (4). Side reactions resulting in the formation of coke may also occur by decomposition of methane (3) or by the Boudouard reaction (5).

Partial oxidation with integrated water gas shift (ATR) or without water gas shift (POX) is mainly governed by oxidation reaction (6). The side reactions such as complete oxidation of methane to CO_2 and water (7) and oxidation of formed CO and hydrogen may also occur in reaction (8) and (9).

The extent of conversion by main reactions to desired products hydrogen (and CO) is dependent on the reaction conditions (temperature and pressure). Broadly, endothermic reactions (1-3) are dominant at high temperatures, and exothermic reactions (4-9) are dominant at lower temperatures. The extent of product formation is governed by the temperature of the reactions and possible removal of products[10]. The increase in the pressure for main reactions is not thermodynamically favourable due to the high number of molecules formed at the product side of reactions. Nonetheless, to improve economics and reduce equipment size, reforming reactions are still operated at high pressures (20-50bar for SMR, and 1-80bar for ATR and POX).[11]

Reforming natural gas to low-carbon hydrogen consists of three main steps (Figure 1):

1. Pre-treatment and reforming of the feedstock gas.
2. Syngas processing and heat recovery section.
3. H_2 clean-up and CO_2 capture section, including export compressors.

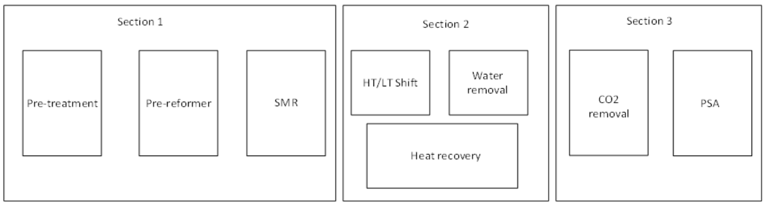

Figure 1: An overview of the three main steps for gas reformation to low-carbon hydrogen.

The complexity (and cost) of the pre-treatment section (section 1) depends on the quality of the gas feedstock used. One of the most important considerations is on the sulphur content of the gas from molecules such as H2S and mercaptans. Sulphur causes irreversible deactivation when it comes into contact with reformer catalysts, as such it is typically removed down to a concentration <1 ppm. This is achieved by running the feed through a hydrodesulfurisation reactor followed by a ZnO guard bed. Refinery fuel gas contains significant amounts of H2S compared to natural gas, so this is an important design consideration. Additionally, the design should take 'upset scenarios' into account (i.e. situations in which the H2S concentration is high for a short period of time, due to abnormal operation of one of the units producing fuel gas).

[10] Moulijn, J. A., Makkee, M., & Van Diepen, A. E. (2013). Chemical process technology. John Wiley & Sons.
[11] Elegancy project D5.2.2 Needed H2 production facilities, integration in port infrastructure, possible ownership structure and CAPEX/ OPEX estimates 2019

SMR with CCS

With respect to the carbon capture integration possibility with a reforming process, there are different options available for a SMR case, as indicated in Figure 2. To maximise the CO_2 emission reduction from an SMR, the CO_2 capture unit should treat the flue gas from the reactor. The CO_2 capture rate constraints of a SMR unit are mainly due to the furnace. The flue gas has a relatively high concentration of CO_2, generally >20mol%, or around double of that from coal fired power plants, owing to the recirculation of CO_2-rich PSA off-gas to the furnace.

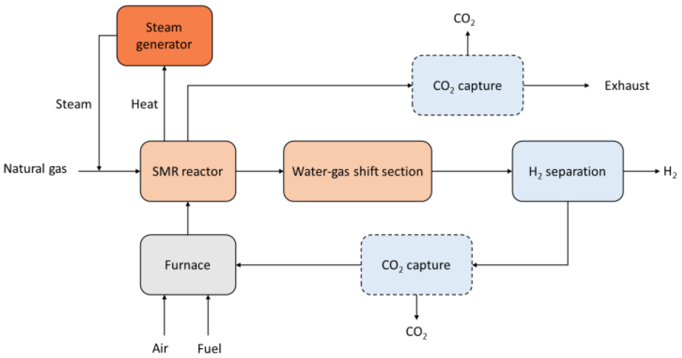

Figure 1: Simplified flowsheet of a traditional SMR, showing two possible locations for CO2 capture.

ATR with CCS

Auto-Thermal Reforming (ATR) is in principle one reactor where natural gas is partially oxidised in a combustion zone, while steam is injected in a reforming zone. Hence, both the partial oxidation and reforming reactions are active simultaneously. The ATR concept in Figure 3 needs pure O_2 input as well as a catalyst bed in the steam reforming section of the reactor. The core benefits of this system are that the heat generated by the partial oxidation reaction is consumed by the endothermic reforming reaction and the units are easily scalable to large capacities.

The combination of exothermic and endothermic processes results in a more energy-efficient process. This enables a closed system, insulated from external heat supply. The oxygen-blown ATR requires a relatively costly air separation unit for oxygen production. However, the absence of nitrogen in the process streams makes the flue gas more CO_2 rich and, as such, CO_2 capture and compression/liquefaction easier to carry out with the oxygen-blown ATR process compared to SMR. As such, higher capture rates (>95%) can be reached without significant impact on costs[12].

With POX, fuel is partially combusted in a reformer with sub-stochiometric amounts of air. With this method, any liquid or gaseous hydrocarbons, e.g. heavy hydrocarbons such as residual oil or diesel, can be used for producing hydrogen. The process is exothermic and can be carried out both with and without catalyst. Oxygen, either pure or enriched, is commonly used in the process which avoids the processing of downstream nitrogen. As such POX operates on the same principle as ATR with CCS, without the water-shift phase.

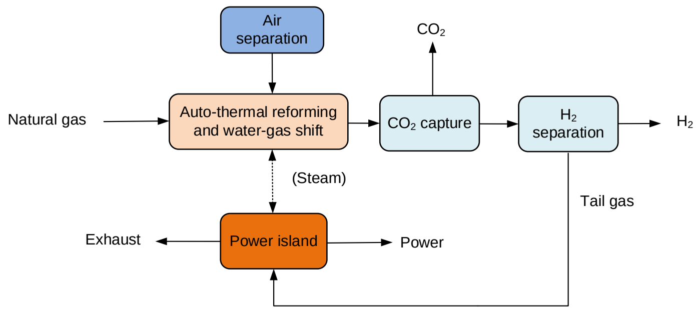

Figure 2: Simplified flowsheet of an oxygen-blown ATR with CO2 capture.

Key Performance Indicators (KPI) for reformation

Key Performance Indicators are used to highlight where additional R&D can improve efficiency and reduce cost of emerging and established technologies. Importantly, reformation of hydrogen is well understood and applying CCS to reformation technologies can be done and is done today with no technical barriers.

The CO_2 capture rate, CO_2 intensity, reformer

[12] H21 2018. H21: North of England Report. Available at: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf

efficiency, and finally, the cost of CO_2 avoided are the most important KPIs for a reformer project, against which the technical concepts will be evaluated. The most critical design parameters that influence the process against these objects are:

- Pre-treatment of Refinery Fuel Gas
- Methane slip reduction via challenging process conditions
- Steam-to-carbon ratio, innovative ATR designs and potential new catalysts
- Innovative system integration and steam heat regeneration
- Challenging evaluation Gas Heated Reformer or high-pressure steam generation
- Shift converter configuration ultra-low CO concentration in product gas
- No Pressure Swing Absorption (PSA) for hydrogen purification needed for high temperature heating applications
- Choice of CO_2 capture technology including the low energy demand concept

2.2. Electrolysis

Renewable hydrogen can be produced from water via electrolysis using renewable energy such as solar and/or wind energy. Electrolysis of water in principle uses a DC current connected to two electrodes to decompose water into hydrogen and oxygen. Thus, electric energy, generated with solar and wind technology, is converted to chemical energy, in the form of hydrogen. Currently there are three different types of electrolysis technology available on the market (alkaline, PEM, SOEC), which all use the same principle, but vary in: efficiency; stack size; operating pressure and temperature; available operating experience; degradation behaviour and required plot space (land-use). Additionally, the produced oxygen can be either sold or released as a harmless emission.

Alkaline

Alkaline water electrolysis is a well-founded, commercially available, and most mature technology for electrolysis. The used electrolyte is an aqueous potassium hydroxide solution. With proper maintenance, lifetimes of 50 to 60 years could be reached for industrial plants – the alkaline systems are robust and highly reliable. Compared to PEM technology there are slight disadvantages concerning area demand, part load behaviour, purity of the produced hydrogen and response times.

Polymer Electrolyte Membrane (PEM)

Polymer Electrolyte Membrane electrolysis in principle uses the same conditions as usual alkaline electrolysis, however, it introduces a solid electrolyte membrane to conduct protons and accelerate the separation of product gases.

The major advantage of the PEM technology is the compact design and the high current density of these cells, which lead to a significant reduction of the area demand and operational cost for PEM installations. Also, the reported response times are extremely fast, and the part load behaviour allows operation from 0 to 100% of its nominal capacity, which makes PEM more suitable for intermittent electricity sources (such as solar and wind generation). The compact design also benefits the development of pressurised cells, which could provide the produced hydrogen at pressure levels of up to 100 bar, without the use of additional compressors. In general, the purity of the produced hydrogen is very high.

Due to the fact that the membrane is used as a solid electrolyte, PEM does not require liquid electrolytes (potassium hydroxide solutions), which are difficult to handle and pose a potential threat for the environment and operators if not properly maintained.

PEM technology has been commercially available for many years but just recently has reached an industrial scale, therefore in most cases the first commercial application are prototypes, which shows that the technology is not as mature as the alkaline technology mentioned above and real operating experience has not been gained yet.

A major disadvantage of this technology is the relatively high CAPEX – for the catalysts which are coated on the membrane, significant amounts of precious metals are required and other expensive materials are used for the stack production and the uncertain degradation behaviour, which is not completely proven yet. The development of this technology is still ongoing and further improvements on costs, reliability and efficiency are the main objectives for the coming years.

Solid Oxide (SOEC)

Solid oxide electrolysis cells (SOEC) are the newest technology. Instead of liquid water, steam is used as a raw material for the water splitting. The steam is also used to heat up the stacks to the required temperature levels, which allow significant power savings and therefore the best efficiencies of the compared Alkaline and PEM. SOEC technology is in an early phase of commercial deployment, first pilots in the 100 kW scale were commissioned, for example the 720 kW SOEC electrolyser used in the GrInHy2.0 project in Germany[13].

[13] https://www.green-industrial-hydrogen.com/

3. Cost of hydrogen production

Chapter 3: Key Messages

The cost of hydrogen production will mainly be driven by operational cost, specifically the feedstock cost.

- The main cost for low-carbon hydrogen produced with CCS is the gas feedstock (natural gas or biogas). With minor additional operational costs to account for the CO_2 capture process.
- Renewable hydrogen production's feedstock cost is considerable amounts of renewable electricity, which in the near-term will result in higher operational costs, expected to fall over time as renewable generation grows and technologies improve.
- Associated infrastructure costs for renewable hydrogen production are higher as vast amounts of renewable capacity and electricity network upgrades will be required to power production.

The production cost of hydrogen will be majorly driven by operational cost[14] :

- Availability of low-cost power will be higher in assets co-located with offshore wind, which will have access to surplus generation, resulting in lower overall hydrogen production cost.
- However, the cost of transportation is expected to be higher for these assets due to the higher distance from demand centres.
- Similarly, for low carbon hydrogen production, the variable cost of gas will be the most significant factor in terms of overall production costs.
- The cost of transportation will also be a significant element of the final delivered cost.

As such, the production costs of hydrogen depend on the feedstock costs, efficiency and capital and operation costs. Neither renewable hydrogen nor low-carbon hydrogen (notably fossil-based hydrogen with carbon capture) is cost-competitive against the current fossil-based energy carriers or feedstocks such as natural gas. If hydrogen is to realise its potential to be an energy vector in a decarbonised economy, it needs to be produced on a mass scale in a low-carbon way, but in order for that to happen, clean hydrogen needs to become cost-competitive with conventional fuels[15]. Below in figure 4 an overview of the different production cost curves is given.

[14] Aurora Hydrogen in the GB energy system 2020
[15] Strategic Research and Innovation Agenda Final draft version July 2020

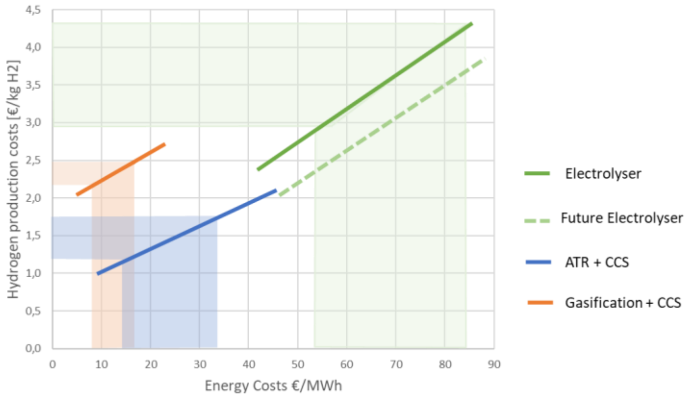

Figure 3: Cost curve of hydrogen production technologies, derived from the H21 North of England project[16]

The application of hydrogen as an energy source requires technology adaptations and infrastructure, which both need to be taken into consideration in the total sum of costs.

Estimated costs today for fossil-based hydrogen with carbon capture are around 1.5 €/kg for the EU, highly dependent on natural gas prices and renewable hydrogen 2.5-4.5 €/kg. Carbon prices in the range of EUR 55-100 per tonne of CO_2 would be needed to make fossil-based hydrogen with carbon capture competitive with fossil-based hydrogen today.

The cost of production of hydrogen is variable across current member states, as access to more reliable renewable electricity sources varies, as does access to natural gas supply and suitable infrastructure. Nonetheless, as shown in figure 5 from Hydrogen Europe the cost of electrolysis across Europe is higher than for reformation, with the range represented in the figure giving a good approximation of the potential costs for ATR+CCS outlined in figure 4 above.

It is vitally important to consider the operational time or 'load factor' of production facilities when considering cost and value. For reformation technologies with CCS, the plants can operate almost continuously provided a reliable feedstock of natural or biogas, with the only downtime required for routine maintenance. For electrolysis production methods, load factor and production are highly dependent on renewable electricity supply, which is dependent on weather, and is especially prone to shortage of supply and low load factors as renewable capacity is expanded. This variable load factor for electrolysis results in much higher average unit costs per hour than for low-carbon hydrogen production. However, as renewable capacity expands, this is expected to drop[17] [18].

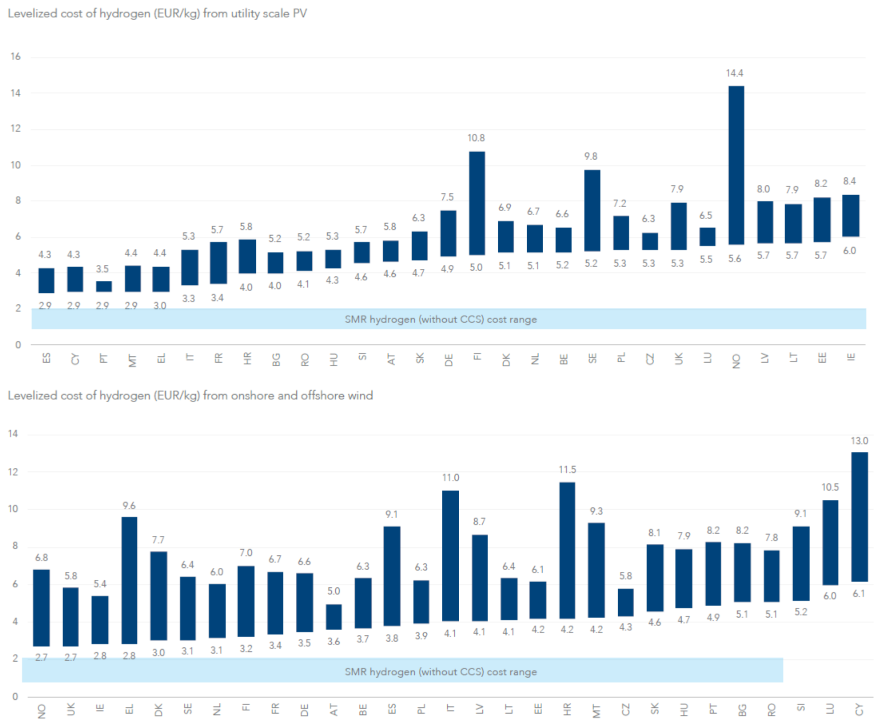

Figure 4: Levelised costs of hydrogen production from electrolysis using renewable sources. The SMR without CCS range in this figure is a good approximation of ATR+CCS costs from the H21 North of England Report[19] and EU Hydrogen Strategy[20]. Source: Hydrogen Europe 2020[21], Clean Hydrogen Monitor

[16] H21 2018. H21: North of England Report. Available at: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[17] H21 2018. H21: North of England Report. Available at: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[18] European Commission ASSET Project, July 2020 Hydrogen generation in Europe: Overview of Costs and Key Benefits
[19] H21 2018. H21: North of England Report. Available at: https://www.h21.green/wp-content/uploads/2019/01/H21-NoE-PRINT-PDF-FINAL-1.pdf
[20] EU Hydrogen Strategy
[21] Hydrogen Europe, 2020. Clean Hydrogen Monitor 2020.

3.1. Costs of hydrogen storage

As investigated in Chapter 1.3, hydrogen storage is an essential component of any hydrogen projects across production, distribution and end-use. Costs of hydrogen storage are an inevitable consideration for any hydrogen production project, and it has been estimated that investment costs (CAPEX) of 334 EUR/MWh of hydrogen stored can be achieved for salt caverns with a levelised cost of storage (LCOS) of 6-26 EUR/MWh of hydrogen stored. For depleted gas fields CAPEX costs of 280-424 EUR/MWh hydrogen stored have been estimated giving 51-76 EUR/MWh LCOS. Other technologies such as rock cavern storage, aquifer storage and LNG terminal repurposing are less well defined from a cost perspective and under active investigation from projects[22].

Hydrogen Europe has estimated in its report[23] that approximately 3 Mt of hydrogen needs to be stored. If each salt cavern stores an average of 6,000 t hydrogen, 500 caverns are needed. The investment costs per cavern is in the range of EUR 100 million, which could total up to approximately EUR 50 billion.

[22] BNEF. 2019. Hydrogen: The Economics of Storage. Available at: https://www.bnef.com/core/insights/21015
[23] Green Hydrogen Investment and Support Report, Hydrogen Europe (2020)

4. Scaling up hydrogen production

Chapter 4: Key Messages

- Hydrogen produced from SMR is already done on an industrial scale today. Fitting carbon capture to methane reformers (SMR and ATR) has the potential to produce several GW of production capacity which can operate at high loads in the 2020s.
- To reach an equivalent GWs level of hydrogen production, renewable hydrogen will require a substantial associated infrastructure development, with a land footprint several orders of magnitude greater than reformation with CCS. Currently, this technology will take longer to scale-up to meet industrial demand.

Hydrogen production is already available on an industrial scale. However, the current fossil-based hydrogen production is responsible for large CO_2 emissions. Exploiting the existing scale of hydrogen production on the way to a sustainable energy future requires both the capture of CO_2 from fossil-based hydrogen production and greater supplies of renewable energy for the production of renewable and low-carbon hydrogen.

The scale up of hydrogen from an unabated fossil-based activity today to a low-carbon and renewable production-based future in 2050 presents a unique challenge to the energy system, which has not been required at such pace and scale before. The International Energy Agency (IEA) have identified seven key steps to scale up the industry, which will present unique challenges for each nation and region. (Box 3).

Considering routes to scale up quickly, it is helpful to compare the infrastructure and building required to fulfil a typical industrial demand. For example, a typical high voltage distribution cable (HVDC) connection can transfer 4 GW of energy at approximately 12.5TWh/year. Figure 6 below highlights the different scale of construction required to supply enough energy through different hydrogen production methods each equivalent to one HVDC connection.

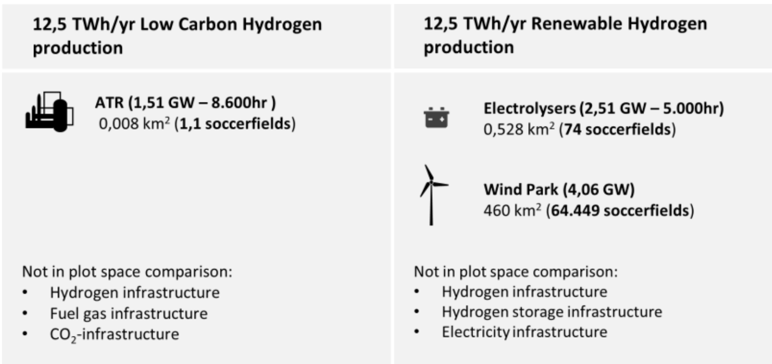

Figure 5: A comparison of the scales of construction required to achieve hydrogen production of 12.5TWh/yr (equivalent energy to a 4 GW High Voltage Distribution Cable (HVDC))

Box 3: IEA 7 Key recommendations to scale up hydrogen from the IEA[1]:

1. **Establish a role for hydrogen in long-term energy strategies.**
National, regional, and city governments can guide future expectations. Companies should also have clear long-term goals. Key sectors include refining, chemicals, iron and steel, freight and long-distance transport, buildings, and power generation and storage.

2. **Stimulate commercial demand for clean (renewable and low-carbon) hydrogen.**
Clean (renewable and low-carbon) hydrogen technologies are available, but costs remain challenging. Policies that create sustainable markets for clean (renewable and low-carbon) hydrogen, especially to reduce emissions from fossil fuel-based hydrogen, are needed to underpin investments by suppliers, distributors, and users. By scaling up supply chains, these investments can drive cost reductions, whether from low-carbon electricity or fossil fuels with carbon capture, utilisation, and storage.

3. **Address investment risks of first-movers**.
New applications for hydrogen, as well as clean (renewable and low-carbon) hydrogen supply and infrastructure projects, stand at the riskiest point of the deployment curve. Targeted and time-limited loans, guarantees, and other tools can help the private sector to invest, learn, and share risks and rewards.

4. **Support R&D to bring down costs.**
Alongside cost reductions from economies of scale, R&D is crucial to lower costs and improve performance, including fuel cells, hydrogen-based fuels, and electrolysers (the technology that produces hydrogen from water). Government actions, including the use of public funds, are critical in setting the research agenda, taking risks, and attracting private capital for innovation.

5. **Eliminate unnecessary regulatory barriers and harmonise standards.**
Project developers face hurdles where regulations and permit requirements are unclear, unfit for new purposes, or inconsistent across sectors and countries. Sharing knowledge and harmonising standards is key, including for equipment, safety, and certifying emissions from different sources. Hydrogen's complex supply chains mean governments, companies, communities, and civil society need to consult regularly.

6. **Engage internationally and track progress.**
Enhanced international cooperation is needed across the board but especially on standards, sharing of good practices, and cross-border infrastructure. Hydrogen production and use need to be monitored and reported regularly to keep track of progress towards long-term goals.

7. **Focus on four key opportunities to further increase momentum over the next decade.**
By building on current policies, infrastructure, and skills, these mutually supportive opportunities can help to scale up infrastructure development, enhance investor confidence and lower costs:
    - Transfer most of the existing industrial ports into hubs for lower-cost, lower-carbon hydrogen.
    - Use existing gas infrastructure to stimulate new clean (renewable and low-carbon) hydrogen supplies.
    - Support transport fleets, freight, and corridors to make fuel-cell vehicles more competitive.
    - Establish the first shipping routes to kick-start the international hydrogen trade.

The scale in hydrogen production capacities of the different hydrogen production technologies differs significantly. The graph presented in figure 7 is based on the state of the art of the different presented hydrogen production technologies using public data from the IEA Hydrogen projects database. The electrolyser technologies are not yet at the required scale of commercial deployment with enough renewable electricity capacity for the necessary hydrogen volume required to achieve the projected energy transition pathways. Also, the technology readiness of electrolysers is at an early stage of development. As such, the production capacity is relatively low compared to the other current fossil-based production technologies.

To be able to produce the required large volumes of hydrogen, low carbon fossil-based technologies are needed. They will play a vital role in the energy infrastructure modifications, minimise investment risks of first-movers, create early hydrogen markets and increase momentum over the next decade.

The projects presented in annex A of this report highlight some of the projects ready to deploy in member states and internationally which are capable of supplying material volumes of low-carbon hydrogen in the 2020s. These projects and technologies are often not in early feasibility or pilot scale and represent real key projects which can offer decarbonisation opportunities for end users, such as heavy industry, in the 2020s.

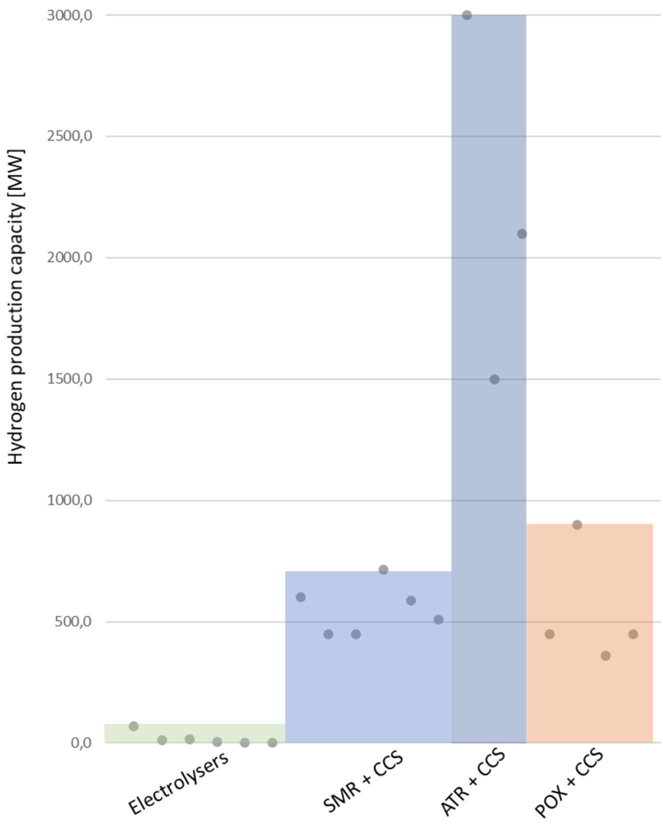

Figure 6: Hydrogen production capacity based on current day state of the art production methods in the IEA Hydrogen projects database[24]

[24] IEA, 2020. Hydrogen Projects Database. Available at: https://www.iea.org/reports/hydrogen-projects-database

5. The crucial role of low-carbon hydrogen in member state energy systems

Chapter 5: Key Messages

- From a member state energy system development perspective, the ambition is to see renewable hydrogen dominate over time, as renewable generation capacity is built and energy networks upgraded.
- A case study from Germany shows that hydrogen ambitions with balanced energy systems can only realistically be met with both renewable and low-carbon hydrogen production technologies, including a critical role in the 2020s to 2040s for low-carbon hydrogen with CCS.

A key consideration for the production at scale of renewable hydrogen will be the development of sufficient dedicated renewable electricity. From a North West Europe perspective, it is broadly assumed that offshore wind (at an increasingly competitive cost) will provide the supply of renewable electricity to be used in the electrolysis process. This may take a considerable amount of time to develop.

Outlined below are two such cases, reviewing the energy system of and Germany it is clear that a disconnect between renewable generation availability and hydrogen ambition exists out to 2040. Hydrogen production from low-carbon sources will be critical for both nations to achieve hydrogen ambition and provides an important value proposition (Box 4).

Box 4: Value proposition of low-carbon H_2 for member state energy systems:

- Early deployment possible (by 2030)
- Can provide a reliable, material volume of hydrogen in the 2020s and 2030s
- Material amount of CO_2 abated by 2040s
- Can be provided on demand or synchronised with energy system demands
- Sends positive market signal to end-use demand and stimulates investment
- With minor retrofit costs, can utilise a well-developed energy infrastructure network through gas pipelines
- Paves-the-way for renewable hydrogen by developing a hydrogen market, regulation, and infrastructure
- Aligns with Energy System Integrated Strategy:
  - Synergies and economies of scale with CO_2 transport and storage infrastructure.
  - Enables sector coupling and lowest cost pathways to decarbonisation.
  - Helps reduce demand on an expanding renewable electricity sector, enabling more strategic energy network planning and infrastructure upgrading.

Germany's hydrogen pathway

In the year 2019, the share of renewable energies in total gross electricity consumption has increased to 42.6%[25] i.e. 243 TWh electrical energy. According to Germany's strategy, that share should increase up to 65% until 2030 which requires an annual growth of 5 GW generation capacity. This rate of capacity growth was met between 2014 and 2017 but has since slowed. For example, in the first half of 2020, 18 new wind power plants totalling approximately 587 MW capacity have been commissioned. This equates to net power of only 528 MW when decommissioning of old wind installations is considered.

When considering the total primary energy demand across all sectors, the share of renewable energy was only 14.7% [26]in 2019, this reinforces the gulf between strategies and reality. As such, this raises the question; How can the German energy system account for the remaining 85.3% primary energy out to 2050 in a climate-friendly, secure and affordable way? One possible answer could be a comprehensive and quick electrification of all sectors. But this requires an equally comprehensive expansion of renewable energies and power grids as well as a conversion of all previously non-electrical applications to purely electrical applications. However, it is already apparent today that rapid and comprehensive direct electrification of all applications in all sectors will be unfeasible. Taking North-South electricity-grid connections as an example, the necessary expansion would take at least 15 years alone[27], and would also require the necessary social acceptance.

Both the expansion of wind power capacity, especially onshore, and the expansion of electricity-grids are stagnating due to limited available land, public protests and long permitting procedures. Electrification can only be implemented as quickly as the expansion of renewable energy.

Ultimately, decarbonised gas (using low-carbon hydrogen) will play a critical role whilst electrification progresses. In 2015, approximately 55 TWh [28]hydrogen (approx. 1.7 Mt hydrogen) was consumed in Germany. Almost 50% was taken for ammonia and methanol production, with a further 40% used in the refinery industry. In the 2020 German National Hydrogen Strategy[29], the 2030 hydrogen demand is estimated somewhere between 90 and 110 TWh for which only a small proportion (14 TWh) is supplied by renewable hydrogen.

This raises a large disconnect between ambition and capacity and provides a supply gap for hydrogen. The remaining 76 to 96 TWh of hydrogen is unlikely to come from imported renewable sources alone. To fulfil the demand by renewables alone is improbable due to the long construction time and high costs of building a vast amount of renewable power generation, electrolysis capacity and associated infrastructure.

It becomes logical therefore that by harnessing the well-developed natural gas infrastructure and CCS projects particularly prevalent in Northern Europe, low-carbon hydrogen can be deployed relatively quickly and provide early volumes of hydrogen for import into Germany.

Hydrogen will fit perfectly into the energy "eco-system" of, but not limited to, Germany. Low-carbon hydrogen can help to fill the gap between primary energy demand and supply and help the slow expansion of renewable energies capacity. It must be noted that the year 2030 is just 9 years away from today.

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[25] Agora Energiewende (2020): Die Energiewende im Stromsektor: Stand der Dinge 2019
[26] AGEB AG Energiebilanzen e.V. 2020: Energieverbrauch in Deutschland im Jahr 2019
[27] Bothe, D. (2019), Indirekte Elektrifizierung mittels eFuels, S. 125 ff., aus: Maus, W. (Hrsg.) (2019), Zukünftige Kraftstoffe, Berlin
[28] National Hydrogen Strategy of Germany 2020: Nationales Reformprogramm 2020 - Die Nationale Wasserstoffstrategie (bmwi.de), last download: 7 Dec 2020
[29] National Hydrogen Strategy of Germany 2020: Nationales Reformprogramm 2020 - Die Nationale Wasserstoffstrategie (bmwi.de), last download: 7 Dec 2020

6. Reducing CO_2 emissions with hydrogen

Chapter 6: Key Messages

- Hydrogen production from electrolysis has a variable carbon footprint depending on the region of production across the EU. Currently, in most places in the EU, electrolysis produced hydrogen using network electricity has a higher carbon footprint than low-carbon hydrogen with CCS – including upstream emissions.
- As electricity grids in Europe decarbonise, electrolysis produced hydrogen's carbon footprint will reduce.
- Low-carbon hydrogen with CCS will play a critical role in the short term to reduce emissions as the wider energy electricity system decarbonises.
- A delayed or small-scale deployment of low-carbon hydrogen with CCS in the 2020s and 2030s could result in a greater total CO_2 emission as end-users will continue to use unabated fossil fuels, or use electrolysis produced hydrogen using carbon intensive electricity grids.

The overall climate impact of a given type of hydrogen depends largely on its method of production[30]. While the efficiency of the hydrogen use also influences its final climate impact, hydrogen can only serve as a climate change mitigation tool when it is produced in a low-carbon way. In any hydrogen production system, the key aspects determining its emissions include the source of energy driving the hydrogen production process and the raw material used in the process[31].

[30] Valente et al. 2020. Prospective carbon footprint comparison of hydrogen options.
[31] JRC.2020. Life Cycle Assessment of Hydrogen and Fuel Cell Technologies.

Hydrogen production

The two relevant and potentially low-carbon hydrogen production pathways, as described in Section 2 of this report, include conventional hydrogen production technologies (SMR, ATR, POX) with CCS and electrolysis.

Overall, the climate footprint of these technologies varies based on the following factors:

- **SMR/ATR/POX + CCS**[32]:
  - Indirect emissions from natural gas value chain and electricity use.
  - The capture and storage rate of direct emissions from the gas reforming unit (i.e. reactor, separation and any other emissions on site)
- **Electrolysis**[33]:
  - Indirect emissions from electricity use

Including both direct and indirect emissions in both cases is important, as both contribute to the overall climate footprint of the hydrogen produced. If both indirect and direct emissions from hydrogen manufacturing are reduced, processes can positively contribute to emission reduction.[34]

For hydrogen produced via methane reformation, 73-96% of the direct emissions can be mitigated via carbon capture and storage[35]. Indirect emissions connected to the hydrogen production value chain, including fugitive and vented methane emissions and incomplete flaring[36], also need to be minimised in order to produce low-carbon hydrogen. Objectives of the EU methane strategy to reduce fugitive emissions will be crucial in achieving that goal. Until leakage in the natural gas systems is minimised, systems with a high rate of leakage should be excluded from the production of fossil-based hydrogen with CCS in order to avoid high life cycle emissions.

For hydrogen produced via electrolysis, indirect emissions from electricity use can be mitigated by using renewable electricity sources. Having a consistent greenhouse gas emissions threshold which considers the full life cycle GHG emissions footprint of hydrogen can be used to stimulate the development of both low-carbon and renewable hydrogen ahead of unabated fossil hydrogen production.

If renewable electricity use is not ensured, the overall emissions increase significantly. For instance, hydrogen produced using the average electricity grid in Germany (440 gCO_2/KWh) would increase emissions 1.7x times over current hydrogen production or 2.7x times over direct natural gas use in process heating (also can be seen in Figure 8). The figure is produced in gCO_2/MJ of energy of hydrogen, which is a more accurate representation of hydrogen production the gCO_2/kWh which is specifically attributed to electricity generation carbon intensity.

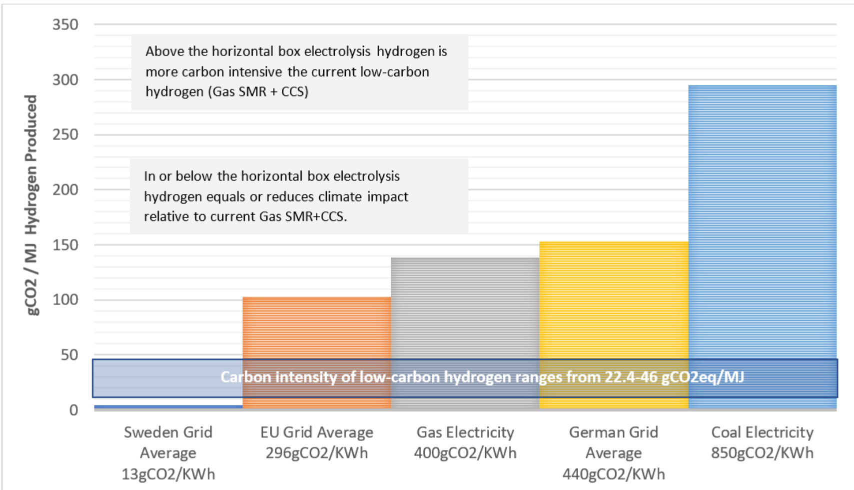

Figure 8: Comparing the carbon intensity of hydrogen produced (gCO_2/MJ) from different electricity generation sources today and of hydrogen produced with SMR+CCS (including upstream emissions).

[32] In this case, it is assumed that the captured CO_2 is permanently stored and therefore isolated from the atmosphere, as outlined in the Directive 2009/31/EC on the geological storage of carbon dioxide.
[15] Technical Expert Group on Sustainable Finance. 2019. Taxonomy Technical Report.
[34] Impacts can also include other environmental impacts, which are relevant for both the CCUS and the electricity-based processes.
[35] JRC. 2017. Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry; IPCC. 2005. IPCC Special Report on Carbon Dioxide Capture and Storage.
[36] IEA. 2020. Methane Tracker 2020.

To maximise emission reductions in hydrogen production, production of hydrogen both from methane reforming with CCS and electrolysis with renewables should be incentivised, particularly in the short term. As electricity grids in Europe become less carbon-intensive, more areas will be able to produce low-carbon hydrogen over time. In the short term however, hydrogen production with CCS is necessary to reduce emissions in hydrogen production on a large scale.

Research indicates that starting with hydrogen production with methane reformation and CCS and gradually shifting to electrolytic hydrogen from renewable electricity will maximise overall emission reductions. According to a study by CE Delft, the carbon footprint of hydrogen from SMR in Norway is 1.14 kg CO_2-eq./kg (in 2015), whereas the carbon intensity of hydrogen from electrolysis is 1.13 kg CO_2-eq./kg (with grid electricity, in 2015).

In areas where the electricity is not yet decarbonised, there is a significant difference between the methane reformation with CCS and electrolytic hydrogen (Figure 9). Hydrogen from SMR in the Netherlands is projected to have a footprint of 1.73 kg CO_2-eq./kg (in 2015), whereas the carbon intensity of hydrogen from electrolysis is 35.01 kg CO_2-eq./kg (with grid electricity, in 2015). The overview in Figure 4 shows the variation in climate impacts between the various hydrogen production scenarios.

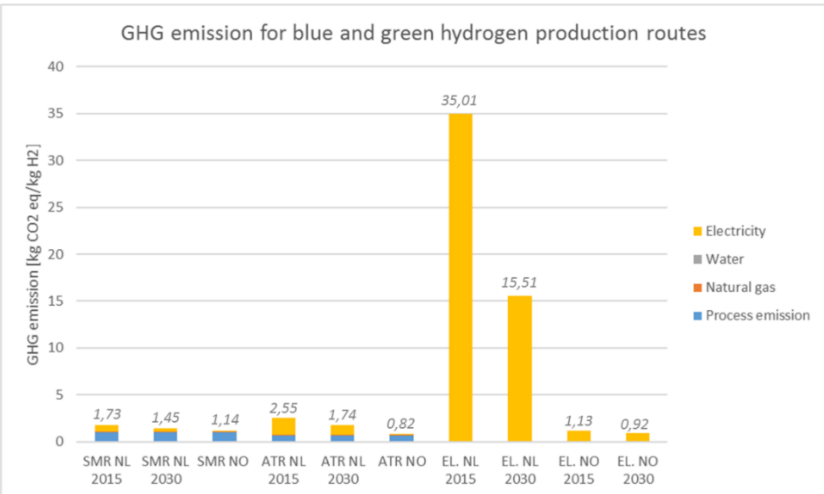

Figure 7: GHG emissions for 'blue'(low-carbon hydrogen) and 'green' (renewable hydrogen) production routes (CE Delft 2018)

According to these estimates, low-carbon hydrogen can significantly contribute to emission reductions in current hydrogen production systems and help solve downstream hydrogen challenges regarding its transport and use.

Biomethane can also potentially be converted to hydrogen and the resulting CO_2 emissions can be captured and stored, resulting in potential carbon removals. However, the overall climate impact of such hydrogen depends heavily on the indirect emissions of the type of biomass used in the process and the CO_2 capture rate, so case-by-case assessments are needed.

Hydrogen use

Due to resource limitations, low-carbon hydrogen production will be of limited scale when compared to the overall climate change mitigation challenge[37]. Consequently, early hydrogen volumes need to be directed into maximum decarbonisation value and into sectors and processes where no direct use of electricity is applicable. For instance, the use of low-carbon hydrogen in industrial processes should be prioritised over its use as an energy carrier in road transport[38].

It must be noted that the potential use of low-carbon hydrogen in the short term, depends on different options that can be implemented; as such, it is essential to review and benchmark all possible CO_2 mitigation options on a case-by-case basis.

Often, electricity grid carbon footprints are represented as averages of the grid mix. This does not represent the range of emissions footprints that is dependent on the generation mix at any one time. In times of very high demand and low renewable generation, reliance often falls on flexible fossil fuel capacity also known as marginal plants. Emissions from these plants contribute to the Marginal Emissions Factor and thus the Electricity grid carbon footprint. Electrolysis that is using grid electricity in periods when marginal generation is in force, may result in very high carbon footprints for hydrogen production (>100gCO_2eq/MJ).

The counterfactual to running in marginal periods is turning off the electrolyser facility and reducing operating hours (and hydrogen output). An in-depth analysis of marginal emissions factors would require a comprehensive study at a member state level and is outside of the scope of this report. A truly integrated energy system in Europe will balance demand and supply side electricity and hydrogen production, this will improve over time as networks become more coordinated and less reliant on unabated marginal fossil fuel plants.

Also, the continuous improvement of the energy efficiency of industrial processes and off-gas product recovery must be considered since this significantly changes the overall need for energy. Both electrification and energy efficiency have a significant impact on energy consumption. For industrial companies, these developments are relevant and should be included to provide a realistic view on the short-term and future demand for hydrogen. Therefore, renewable and low-carbon hydrogen is a crucial option for the petrochemical and oil-refining industry to be able to further improve operations and to increase the share of renewable energy via electrification.

[37] ZEP. 2019. Climate solutions for EU industry: interaction between electrification, CO2 use and CO2 storage.
[38] T&E. Roadmap to Decarbonising European Cars.

7. Wider impacts and need for cooperation on infrastructure

Chapter 7: Key Messages

- The development of CO_2 infrastructure is a critical enabler for the hydrogen economy as it facilitates the growth of a low-carbon hydrogen sector in the 2020s and 2030s.
- Repurposing of current infrastructure for use as either hydrogen or CO_2 pipelines is critical to ensure the lowest cost pathway for the deployment of hydrogen.
- Hydrogen backbone infrastructure (including storage) across Europe will initially connect industrial regions and spread, using repurposed infrastructure where possible.
- Volumes of low-carbon hydrogen in the 2020s and 2030s will provide a valuable usage of infrastructure, which over time will transport higher proportions of renewable hydrogen. Without early use from low-carbon hydrogen, hydrogen infrastructure risks becoming under used or stranded assets.

Hydrogen production with CCS is particularly relevant for areas which cannot produce renewable hydrogen due to the high carbon intensity of the grid. These areas, such as in the North-West of Germany and the Netherlands, often house large industrial clusters, where there is potential for direct applications of hydrogen in the steel and chemical/petrochemical industry. Some of the large steel manufacturers such as Thyssenkrupp have already committed to using hydrogen for Direct Reduced Iron (DRI) when it becomes available but have said that their plants will be operated using natural gas until then[39]. Producing low-carbon hydrogen in the next decades can provide a supply of low-carbon fuels to such industries and prevent the unabated use of natural gas in the meantime.

Hydrogen plants with CO_2 capture would need adjacent CO_2 transport and storage infrastructure, which could then also be used for the decarbonisation of energy-intensive industries in the vicinity. Coupled with the shared need for CO_2 transport and storage infrastructure, hydrogen production with CCS would be complementary to the decarbonisation of the local industry in regions such as the Ports of Rotterdam and Amsterdam in the Netherlands or North-Rhine Westphalia. Annex A highlights a number of projects which are preparing to be operational in the 2020s and produce material volumes of low-carbon hydrogen, co-located with proposed CCUS cluster development and CO_2 infrastructure.

To ensure that hydrogen can be deployed at scale in Europe before 2050, investment in this CO_2 infrastructure will be required[40]. Cross-border CO_2

[39] S&P Global. 2020. Germany's Thyssenkrupp to build DRI plant run on hydrogen for green steel production.
[40] Material Economics, 2019. Industrial Transformation 2050. Pathways to Net-Zero from EU Heavy Industry. Available at: https://materialeconomics.com/material-economics-industrial-transformation-

transport and storage infrastructure will connect industrial clusters – including low-carbon hydrogen production facilities, creating an infrastructure backbone to which industrial emitters could plug in to benefit from the applications for CCS. This shared CO_2 transport and storage infrastructure is the ultimate European project, a strategic and instrumental policy decision; safeguarding jobs, industrial activity and economic growth, thus preserving Europe's welfare and future-proofing Europe for a climate-neutral economy.

The economies of scale which can be achieved from the sharing of both CO_2 and hydrogen infrastructure are well understood, and Europe has in place natural gas infrastructure which, once repurposed, can accelerate a transition to a hydrogen economy[41]. Vitally, without CO_2 infrastructure which can enable hydrogen production at scale, a hydrogen economy may struggle to be established in the 2020s and early repurposing opportunities and cost savings may be lost.

The EU Hydrogen Strategy clearly highlights the important role that infrastructure will have for hydrogen and identifies some of the critical potential mechanisms at the Commission's disposal to facilitate infrastructure deployment. The Strategy also notes that CO_2 infrastructure and hydrogen infrastructure are inherently linked especially for the first 'phase' of projects.

Early project deployment enabled by CCS can enable the benefits for hydrogen to be realised and accelerate the deployment of other production technologies, by addressing the inevitable market and regulatory barriers encountered when establishing a new sector.

For hydrogen infrastructure, transportation and storage facilities are essential. Both can be realised by using existing infrastructure and by establishing a new infrastructure.

7.1. Using existing infrastructure and requirements

Using existing infrastructure means to take existing underground storage facilities (salt or pore caverns) and pipelines which have been used both for natural gas and, formerly, for city gas storage and transportation. Injection of hydrogen into running natural gas caverns or pipeline is possible but might cause some technical and commercial issues: as an example, the mixing of hydrogen with natural gas in pipelines can cause fluctuating compositions linked to fluctuating heating values. Some industrial manufacturing processes need constant and high heating values otherwise the product quality cannot be kept at all during the manufacturing process. Consumers of gas with fluctuating heating values pay the price for gas at higher heating value while just receiving gas at lower heating value if there is no appropriate measuring device on site available to adjust the price-heating value interaction.

Assessments on a case-by-case basis will determine if retrofitting of the related facilities for 100% hydrogen is the most cost-efficient pathway. Prior to use for hydrogen, natural gas pipelines need to be checked for leakages and cracks which could lead to stress corrosion by hydrogen, in addition to an analysis of pipeline materials. Often, existing pipelines are of different construction years (decades) when different materials, technical specifications and guidelines were applied. There is ongoing research to understand hydrogen-induced cracks and crack propagation and the key factors which influence a pipeline's stability.

Therefore, a European standardisation of networks and safety regulations is strongly required to avoid mismatches among European states and additional costs.

As an example, the project "H2-PIMS", part of the German funded HYPOS initiative, investigates how to transport hydrogen in the German natural gas

2050.pdf?cms_fileid=303ee49891120acc9ea3d13bbd498d13

[41] Guidehouse, 2020. European Hydrogen Backbone. How a dedicated hydrogen infrastructure can be created. Available at: https://guidehouse.com/-/media/www/site/downloads/energy/2020/gh_european-hydrogen-backbone_report.pdf

grid safely. Additionally, the GET H2 project in Germany is investigating the planning, upscaling and realisation of a local to regional hydrogen network. This first phase of the hydrogen network will be a 130 km pipeline from Lingen to Gelsenkirchen to connect industries (industrial partners include BP, Evonik, nowega, OGE, RWE).

In the UK, the H100 project has appraised gas infrastructure suitability for hydrogen, and projects such as the HyDeploy are testing the domestic deployment of hydrogen including on safety aspects.

In the Netherlands, Gasunie has also been putting many efforts into the set-up of hydrogen infrastructure. Since 2018, a former natural gas pipeline retrofitted to accept hydrogen connects industries in Zeeland and Delta region, and in 2023 the Norther H2 Infra project will connect Eemshaven, Delfzijl, Emmen and several salt caverns. Another example is the large-scale H2M project which plans to establish renewable hydrogen infrastructure in Groningen. Finally, in June 2020 the new project HyWay 27 was announced by the Dutch Government to investigate the retrofit of existing natural gas grids.

In parallel, several gas grid operators are beginning to prepare some existing natural gas pipelines to become hydrogen-ready during maintenance phases or even make sure that new built natural gas pipelines are already hydrogen-ready. In a recent report from gas network operators, a comprehensive cost and technical review of gas pipeline retrofit highlighted that retrofit was a key low-cost enabler of the hydrogen transition[42].

By using existing infrastructure, it is very likely to set-up hydrogen transportation and storage to supply and connect major industrial areas in the Netherlands and Flanders with industrial regions such as Hamburg or the Ruhr area from a very early stage like 2030. An additional benefit of using existing infrastructure, public acceptance might not get a critical issue.

7.2. Estimating of investment costs for hydrogen grids – an approach

Investment costs for hydrogen grids differs from country to country and depend on the type of pipelines (distribution, transmission) and its related pressure and diameter design and the required amount of compressors. For UK, the required investments to set-up new hydrogen pipelines are estimated up to 200 mGBP per year in the 2030s (AURORA 2020[43]). In a study by the German Research Centre Jülich (FZJ)[44] in 2012, some ranges of investment costs to provide a hydrogen network at different countries were given. Depending on the countries boundary conditions which consider the different regional demand for hydrogen, the availability of grid retrofits from natural gas to hydrogen and new built of hydrogen grid, investment costs of EUR 9 billion in the Netherlands, EUR 3.4 billion in the USA and EUR 23 billion in Germany were estimated. It was also pointed out that a cross-border comparison is difficult.

In the recently published report of Hydrogen Europe[45], investment costs for hydrogen infrastructure and storage in Europe are estimated up to EUR 120 billion. The calculation is based on the retrofit of 50,000 km of natural gas grid and on the set-up of 5,000 km of new pipelines. It is assumed that the specific CAPEX of a new pipeline is EUR 1 million[46] per 10 GW pipeline capacity per km pipeline length for pipelines from Eqypt to Greece to Italy. For a first approach, that cost range can be also applied for pipelines on continental Europe.

In Germany, 5,900 km of hydrogen grid, made of

[42] Guidehouse, 2020. European Hydrogen Backbone. How a dedicated hydrogen infrastructure can be created. Available at: https://guidehouse.com/-/media/www/site/downloads/energy/2020/gh_european-hydrogen-backbone_report.pdf
[43] Hydrogen for a Net Zero GB, Aurora Energy Research (2020), internet download 9 Oct 2020
[44] Krieg, D. (2012), Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff, Reihe Energie & Umwelt, Vol. 144, 2012
[45] Green Hydrogen Investment and Support Report, Hydrogen Europe (2020)
[46] van Wijk, A.J.M., Wouters F. (2019), Hydrogen – The Bridge between Africa and Europe, Sep 2019, Internet download 9 Oct 2020

existing natural gas pipelines retrofitted into hydrogen, is proposed. In the Netherlands, a similar plan is proposed: the retrofit of natural gas pipelines into hydrogen plus a minor part of set-up of new hydrogen pipelines is estimated to arise investment costs in the range up to EUR 1.5 billion. If the same extent of grids has to be set-up as new without any retrofitting of existing pipelines, the investment costs are estimated in the range of EUR 5 to 6 billion[47]. Therefore, it is possible to save costs up to 75% by using existing infrastructure.

It has to be pointed out that a cost-efficient and fast set-up of hydrogen infrastructure and its safe, reliable and economic operation requires close European collaboration in a similar way as it has been done at the power and natural gas grids and supply for decades.

The construction of new hydrogen and CO_2 networks, or retrofitting current networks for hydrogen presents an unprecedented challenge for energy system across Europe. The European Commission through funds such as the CEF have mechanisms which will be critical tools to help develop interconnected energy networks, including hydrogen and CO_2 across Europe. As is currently proposed for electricity, it is vital that eligibility for retrofit of current infrastructure, and storage aspects for both hydrogen and CO_2 can be considered by the CEF or equivalent funding.

[47] Green Hydrogen Investment and Support Report, Hydrogen Europe (2020)

8. Conclusion

It is clear that both renewable and low-carbon hydrogen should play a crucial role in the European Green Deal and in achieving both the 2030 and the 2050 climate targets. The European Hydrogen Strategy outlines how the EC will encourage and integrate the hydrogen economy, however the exact pathway to a hydrogen economy – from production, to wholesale markets, regulation and end-use is not clear.

In order for any electricity grid-connected manufacturing of low-carbon hydrogen, regardless of technology, to be defined as sustainable by the European Taxonomy for Sustainable Finance, important issues remain to be addressed to enable the production of low-carbon hydrogen from reformed natural gas with CCS. It is not exactly clear how the current threshold of 2.256 tCO_2eq/t has been designed and whether it will decline over time. Furthermore, the definitions of hydrogen in the EU Hydrogen Strategy create confusion which may have unforeseen consequences when considering hydrogen project development, using EU mechanisms or when considering how projects may qualify under the European Taxonomy for Sustainable Finance. The definitions outlined in the EU Hydrogen Strategy should be attributed to a lifetime GHG-emissions saving and be made consistent across all EU regulation and legislation.

CCS with its shared CO_2 infrastructure enables early, low-carbon hydrogen at scale, which can kick-start a European hydrogen economy, helping to safeguard jobs, industrial activity and economic growth, thus future-proofing Europe for a climate-neutral economy.

It is clear that there is a disconnect between renewable hydrogen ambition and realistic capacity and generation expansion timelines. Enabling early, large volumes of low-carbon hydrogen will provide strong signals to industry and member states to invest in hydrogen infrastructure, supply chains, appliances, and industrial fuel switching. It will also enable member states and the EC to establish the policies and regulatory frameworks needed to drive the development of a European hydrogen economy. This will also pave the way for the scaling-up of electrolysis-produced hydrogen, as renewable electricity becomes more abundant, creating a technology-neutral market, where renewable and low-carbon hydrogen, regardless of technology, can co-exist and compete on equal terms.

8.1 Policy recommendations

Terminology and certification

- **Terminology:** Propose consistent, EU-wide terminology and subsequent classification based on life-cycle GHG emissions savings, covering both renewable and low-carbon hydrogen (as currently defined in the European Hydrogen Strategy).
- **Taxonomy:** Under the EU Taxonomy, important issues remain to be addressed to enable the production of low-carbon hydrogen from reformed natural gas with CCS. It is not exactly clear how the current threshold of 2.256 tCO_2eq/t has been designed and whether it will decline over time. Power Purchase Agreements

– with both temporal and geographical correlation - should be introduced to comply with the electricity threshold.

- **Carbon removals:** A regulatory framework for the certification of carbon removals should be developed. Importantly, this framework should be compatible with the EU ETS in order to incentivise carbon capture from EU ETS installations emitting biogenic CO_2, for example biogas reformation with CCS to create hydrogen with a negative carbon footprint.

Hydrogen and CO_2 infrastructure

- **Infrastructure planning:** Renewable and low-carbon hydrogen infrastructure planning should be integrated into the TEN-E and TYNDP frameworks. In particular, attention should be given to possible synergies between hydrogen and CO_2 infrastructure to achieve low-carbon hydrogen production at large scale while tackling hard-to-abate emissions (e.g. in port areas and industrial clusters). This will deliver early, large-scale volumes of low-carbon hydrogen to industry and homes, encourage industrial stakeholders and national governments to undertake a cost-efficient decarbonisation pathway and kick-start a clean hydrogen economy.
- **Enabling CO_2 and hydrogen storage:** CO_2 storage and hydrogen should be included in the TEN-E Regulation and subsequently as part of the projects which can potentially become eligible for PCI status and CEF funding. CO_2 and hydrogen storage will have an important cross-border dimension, as not all member states have the potential to geologically store CO_2 or hydrogen domestically.
- **Tackling barriers to CO_2 transport:** The recognition of other modes of CO_2 transport than pipeline (such as by ship) under the EU ETS Directive, the Monitoring and Reporting Regulation and the TEN-E Regulation would contribute to tackling remaining regulatory barriers and other issues that challenge the transport of CO_2 to those places where it will be stored or used.

Policy support

- **EU funding instruments:** Relevant Next Generation EU and MFF funding instruments (such as the Recovery and Resilience Facility, cohesion funding, Horizon Europe, Connecting Europe Facility, InvestEU and the Just Transition Mechanism) can further accelerate hydrogen deployment of should consistently support both renewable and low-carbon options.
- **Potential targets or quotas:** If hydrogen targets or quotas in specific end-use sectors are considered, potential impacts should be carefully assessed, and policymakers should ensure that all renewable and low-carbon hydrogen should be eligible to meet any potential targets or quotas.
- Ensure the revision of the **State Aid Guidelines for Environmental Protection and Energy (EEAG)** covers wider CCUS and hydrogen activities in addition to those already represented. Including CO2 transport via modalities other than pipelines and retrofit pipelines for CO2. To enable the development of hydrogen networks, the deployment of low-carbon hydrogen infrastructure and retrofit activities should also be to qualify for state aid should also be able to qualify for state aid under the EEAG.

Research and innovation

- **European Partnership for Clean Hydrogen:** The forthcoming European Partnership for Clean Hydrogen, building on the success of the existing FCH 2 JU, should be broadened to include all end-use sectors, all renewable and low-carbon hydrogen production technologies as well as innovation in business models, processes and market creation in its scope.

- **SET-Plan:** The SET-Plan offers a platform to steer the development of key pilot projects that can support hydrogen value chains in Europe. The EC should ensure that synergies which can be achieved with the SET-Plan TWG9 on CCS and CCU are leveraged.
- **System operators:** TSOs and DSOs should be enabled to undertake a reasonable level of R&I activities and pilot projects (e.g. focusing on CO_2 transport and/or hydrogen injection in the gas system) as part of their regulated activities, without compromising general unbundling principles.

Annex A: Low-carbon hydrogen production projects in the 2020s

The annex showcases the array of different low-carbon hydrogen production projects ready to deploy in the 2020s to supply a material volume of low-carbon hydrogen for industrial uses. This highlights that many projects, particularly co-located in industrial clusters as anchor projects for CCUS clusters, can move and scale to help achieve 2030 climate targets.

A.1. Projects in Europe

H-vision – Port of Rotterdam, Netherlands

The large-scale production and utilisation of low-carbon hydrogen will allow local industry in Rotterdam to substantially reduce its CO_2 emissions, well before 2030[48]. The focus of H-vision is on the production of low-carbon hydrogen using natural gas and refinery fuel gas. The CO_2 that is captured during production will be safely stored in depleted gas fields under the North Sea or used as a building block for basic chemicals such as methanol, for example.

As such, H-vision anticipates the arrival of renewable hydrogen, which is produced via electrolysis using power sourced from sources like offshore wind farms. This means that H-vision can become the seed of a new hydrogen economy in Rotterdam providing an opportunity to develop itself into a major hub for the production, uptake and trading of hydrogen whilst significantly contributing to the achievement of climate objectives.

In H-vision, parties mainly from the Rotterdam harbour and industrial region, represent the hydrogen value chain, from production to end-users. The conclusions of the H-vision feasibility study, published in July 2019[49], show that H-vision can deliver substantial CO_2 reductions in the short term, providing up to 7 TWh of low-carbon hydrogen by 2031 and 3.5 TWh in 2026, abating from 27-130 Mt of CO_2 over the 20-year lifetime of the project (depending on the scale of roll-out).

Parties in this H-vision partnership are: Deltalinqs, Air Liquide, BP, Gasunie, the Port of Rotterdam Authority, Power Plant Rotterdam, Shell, Uniper, Royal Vopak and ExxonMobil.

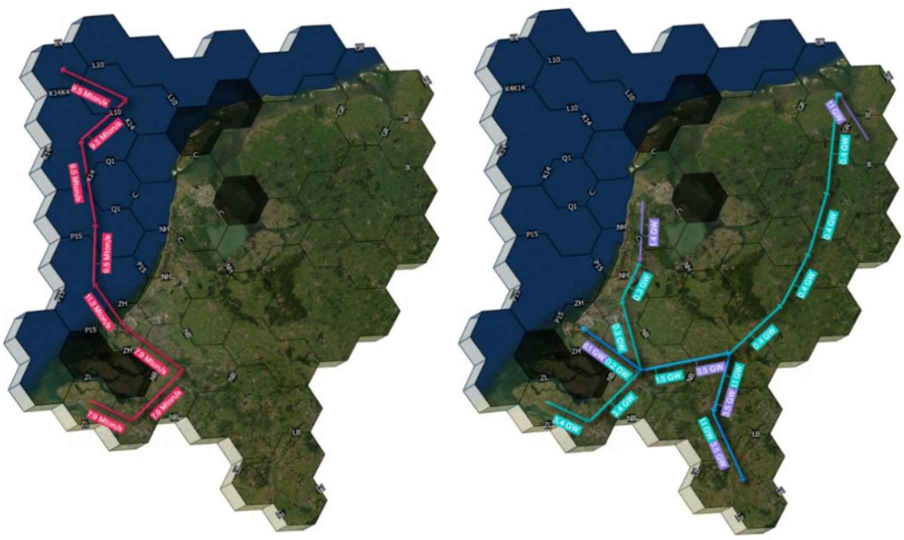

Figure 8: Simulated Dutch network infrastructure in 2030 for CO_2 (left) and Hydrogen and Natural gas (right, routes may overlap) noting the central role hydrogen production at the coastal Rotterdam cluster (West) and at the proposed electrolysis site near Groningen (North).

[48] Elegancy project Dutch case study with the Chain tool 2020.

[49] H-Vision, July 2019. Blue hydrogen as accelerator and pioneer for energy transition in the industry. Feasibility study report. Available at: https://www.deltalinqs.nl/stream/h-vision-final-report-blue-hydrogen-as-accelerator

Northern Lights – CO_2 Storage Network, Norway

The Northern Lights project is the storage phase of the larger CO_2 Longship Project. The Northern Lights business model looks to provide CO_2 transport and storage options via ships to a carefully selected CO_2 storage site and aquifer in the Norwegian offshore. Importantly, this project, which will become operational by 2024, enables coastal emitters to access CO_2 storage even if they are not located nearby, or emitters are relatively isolated and cannot find economies of scale with local industries (in a cluster model)[50].

Figure 9: Shared CO_2 storage concept, highlighting coastal projects storing in the Norwegian offshore (Northern Lights project). From Bellona, Industry in a Changing Climate, 2018[51].

This project has unlocked CO_2 storage services for low-carbon hydrogen projects in several EU projects including:

Preem CCS, low-carbon hydrogen, Sweden

Preem is one of the largest CO_2 emitters in Sweden, and their hydrogen production facility at the Lysekil refinery alone emits 480kt of CO_2 per year (one-third of the sites' 1.5Mt annual emissions). As a coastal emitter with few local CO_2 storage options, the Preem refinery site at Lysekil is investigating connecting to the Northern Lights storage project to capture some of the 1.5Mt of annual CO_2 emissions.

One aspect of the project is to develop CO_2 capture on the hydrogen production unit, initially at demonstration scale, moving to commercial deployment by 2025. The project is in pre-study phase, and is a partnership between Preem, Equinor, SINTEF and Aker Solutions.

[50] Northern Lights CCS. More information at: https://northernlightsccs.eu/
[51] Bellona, 2018. Industry in a changing climate. Available at: https://network.bellona.org/content/uploads/sites/3/2018/11/Industry-Report-Web.pdf

H2morrow, North Rhine Westphalia, Germany

The H2morrow project is a low-carbon hydrogen production project aimed at providing German industry with reliable volumes of low-carbon hydrogen in the 2020s to decarbonise heavy industry and rail transport. Facilitated by Equinor and Northern Lights, the project looks to reform hydrogen at the coast or in the Netherlands and pipe hydrogen inland. The captured CO_2 would then be transported and stored by Northern Lights.

This aims to provide 8.6 TWh per year of low-carbon hydrogen for industrial use by 2030 and abate 1.9 million tonnes of CO_2 per year. Interestingly, a major anchor project for H2morrow is a new Direct Reduced Iron (DRI) steel plant operated by Thyssenkrupp, which is an emerging technology using hydrogen to create 'clean steel'[52].

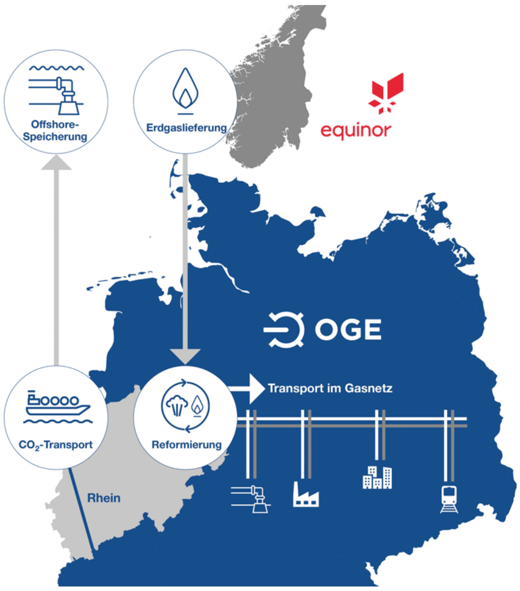

Figure 10: The H2morrow project concept. Producing low-carbon hydrogen for heavy industry in Rhine Westphalia and storing the CO2 in the Northern Lights storage site.

Magnum Hydrogen Power, Netherlands

The Magnum Project is looking to convert a Natural Gas power station at Eemshaven to run on low-carbon hydrogen, with the CO_2 captured from reformation and stored in the Northern Lights storage site or proximally offshore in the Dutch North Sea. The conversion will be modular and address each of the three 440 MW CCGT units incrementally.

The project is in the Feasibility Study stage and when operational will result in hydrogen production primarily for power generation and local industry, resulting in up to 4 Mt of CO_2 captured and stored per year. The project is looking to become operational in the mid-2020s, and represents a partnership between Equinor, Vattenfall, Gasunie and MHPS.

CCS Ravenna Hub, north-east Italy

The CCS Ravenna Hub is a CCS project coordinated by Eni. The project is in the pre-feasibility stage and is looking to use both CCUS to decarbonise the Ravenna industrial cluster, including refining, power generation and hydrogen production. The low-carbon hydrogen produced will be used in local industrial processes, before potentially being expanded for wider industrial and commercial usage.

The captured CO_2 would be transported and stored in large, depleted gas fields in the Adriatic Sea. The project, as a whole, hopes to capture and store up to 5 Mt of CO_2 per year by 2030, and aims to come into operation incrementally over 2025-2028.

[52] H2morrow. More information at https://oge.net/en/us/projects/h2morrow

HyNet, north-west England

The HyNet North West is a hydrogen and CCUS project in the north-west of England, spanning parts of Cheshire, Manchester, and Liverpool. The project is looking to reform natural gas in 3x350 MWh Auto Thermal Reformers, capturing at least 97% of the CO_2 for storage in the depleted Hamilton Field in the nearby East Irish Sea Basin. The early volumes of hydrogen will be provided to 10-15 local industrial users for fuel switching purposes, additionally, hydrogen will be provided for local transport fleets and blended into gas networks. The project is in advanced development and aiming to be operational in the mid-2020s. Later expansions of the project will increase hydrogen production volumes and connect into a wider UK Hydrogen economy on the East Coast of the UK and South Wales industrial regions.

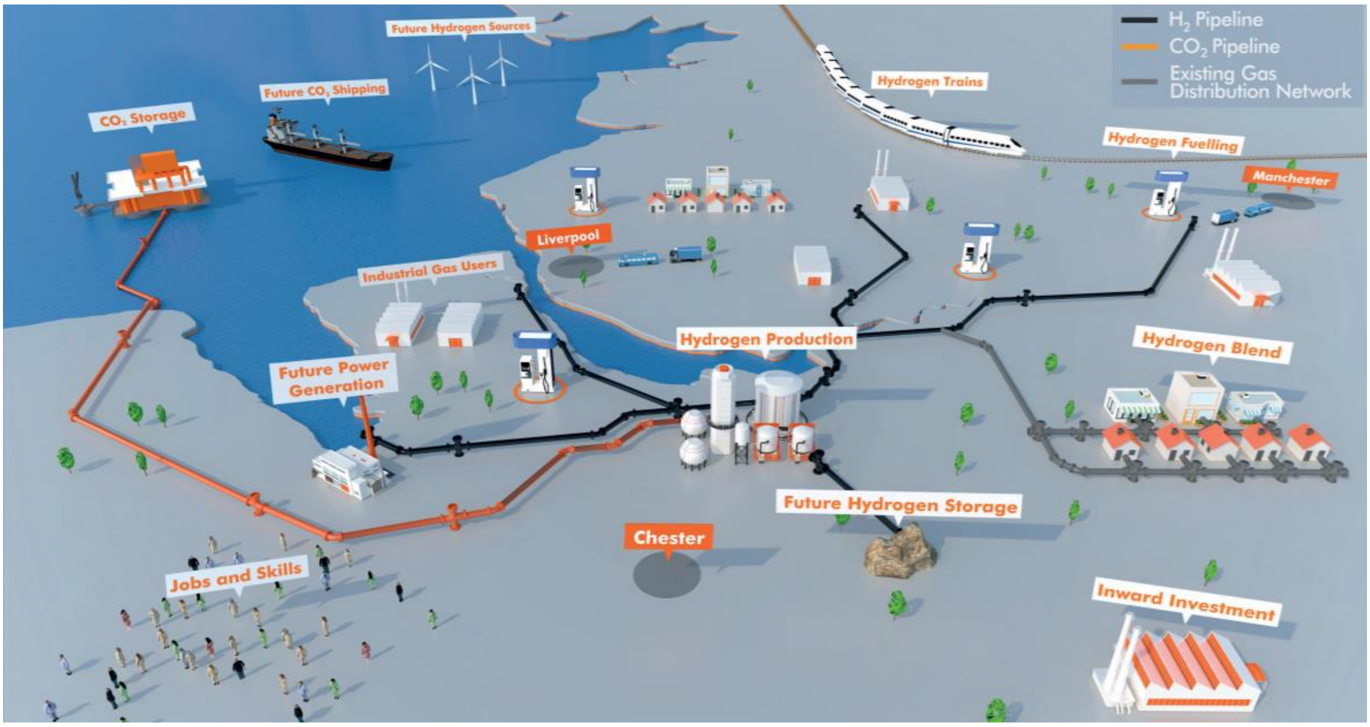

Figure 11: HyNet Project NW England. Highlighting the role of hydrogen and CCS to decarbonise the regional cluster ©HyNet

Saltend H2H, Humberside, England

The Saltend H2H project is a low-carbon hydrogen project at the Saltend Chemicals Park in East England. The hydrogen will be produced from a 600 MW Auto Thermal Reformer fitted with CCS, then blended with natural gas for power generation, or used directly by industry to decarbonise the refinery and chemical plants. The captured CO_2 will be added to a regional Yorkshire/Humber CO_2 network, and stored offshore in the Southern North Sea.

The project plans to expand to include renewable hydrogen as a hydrogen production hub, and is in advanced stages of development, aiming to be operational by 2025.

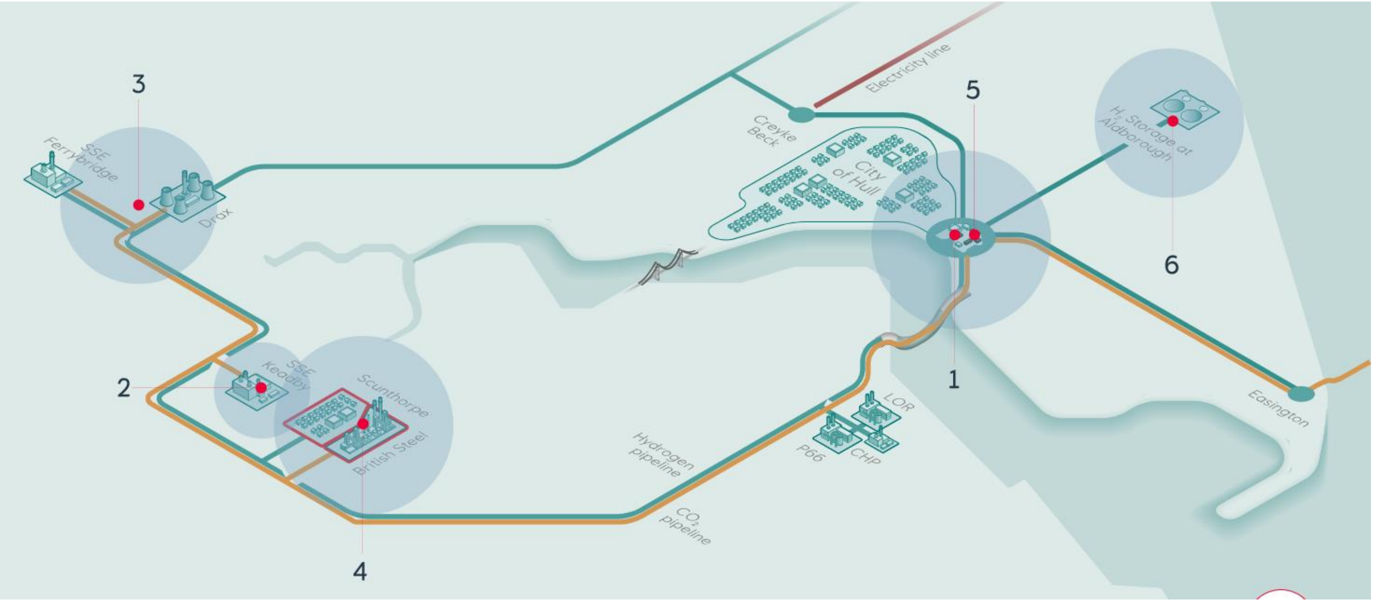

Figure 12: Saltend H2H Project and its role in a decarbonised cluster. 1. Hydrogen production at Saltend. 2. Transmission of hydrogen to SSE Keadby Power Hub. 3. Expansion of hydrogen network towards Drax and Ferrybridge. 4. Hydrogen supplied to British Steel. 5. Renewable hydrogen capacity expands. 6. Development of hydrogen storage53 ©Equinor

[53] Equinor, 2020. H2H Saltend, The First Step to a Zero Carbon Humber. Available at https://www.equinor.com/content/dam/statoil/image/equinor-images/h2h-saltend/equinor-H2H-saltend-brochure-2020.pdf

Acorn Hydrogen, Scotland

Acorn Hydrogen is a project looking to create low-carbon hydrogen at the St Fergus Gas Terminal in Scotland. The Acorn Hydrogen project is one branch of the Acorn CCUS project, which is looking to store captured CO_2 from St Fergus and the Central Valley of Scotland using reused pipelines in depleted fields of the Central North Sea.

The Acorn Hydrogen project is looking to use a 200MW reformer with CCS to create low-carbon hydrogen for local industries, transport fleets and blending into the national gas grid. Phase 1 of the project is in advanced development and aiming to be operational in 2025[54].

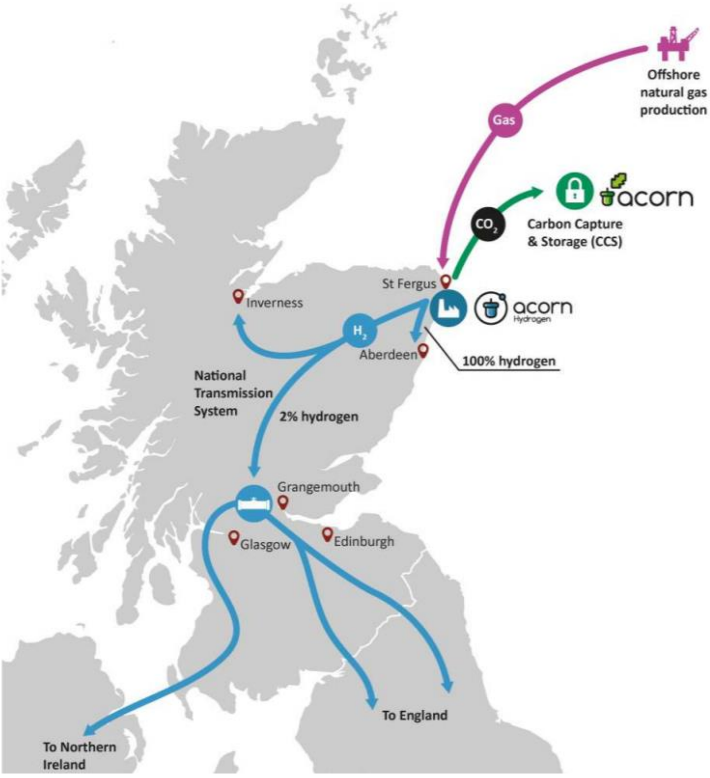

Figure 13: Overview of Acorn Project concept (from Element Energy 2020)

[54]Element Energy 2020. Hydrogen in Scotland: The role of Acorn Hydrogen in Enabling UK Net Zero. Available at: https://theacornproject.uk/wp-content/uploads/2020/09/Hydrogen-in-Scotland-The-role-of-Acorn-Hydrogen-in-Enabling-UK-Net-Zero.pdf

A.2. Projects outside of Europe

ACES – Advanced Clean Energy Storage (Utah, USA)

Ambitious climate targets established in the "Regional Greenhouse Gas Initiative" (RGGI) have initiated large-scale projects in many US federal states like the "Advanced Clean Energy Storage" at Delta, Millard County (Utah).

The project plans to generate electricity from renewable energy and convert it into renewable hydrogen using electrolysers, then store the hydrogen in a network of up to 70 salt caverns and to distribute it via a large pipeline network. A single salt cavern can store hydrogen to generate electricity up to 100 GWh capacity. In parallel, renewable electricity is foreseen to be converted into compressed air and stored also in salt caverns. When there is need for electricity, the compressed air can be discharged through expanders and the stored hydrogen is foreseen to be used in gas turbines and fuel cells – both to generate power.

This is linked to another large-scale project of Intermountain Power Agency at Delta to retrofit its coal-fired power plant into a gas-fired power plant from 2025. The gas-fired power plant will be transformed step-wise from natural gas to hydrogen usage, also connected to the hydrogen infrastructure of ACES and can supply power up to 840 MW.

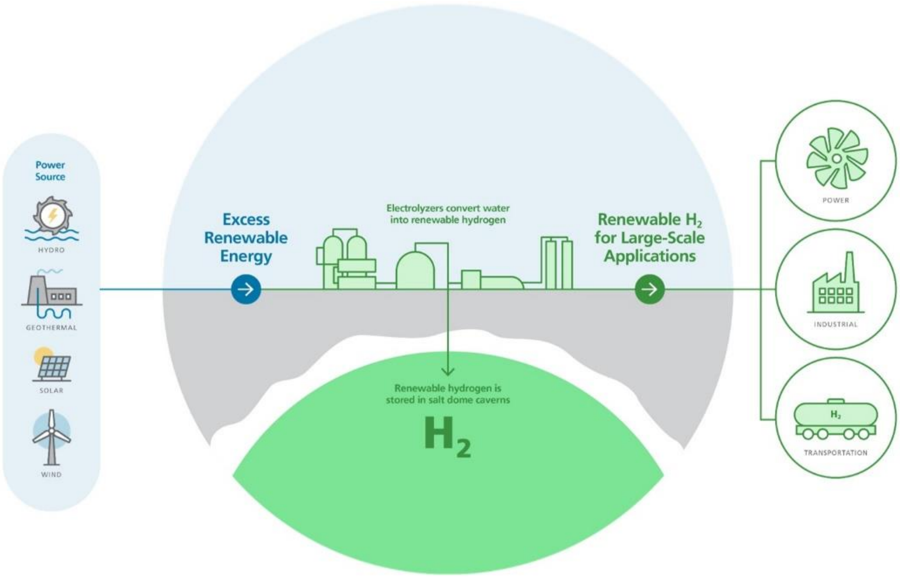

Figure 14: Advanced Clean Energy Storage, Utah. Schematic © Mitsubishi Power

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