REPORT 2020

On the Role of Nuclear Power in the Development of a European Hydrogen Economy

Executive Summary

In July 2020, the European Commission published A Hydrogen Strategy for a Climate-Neutral Europe, intended to complement and support both its Energy System Integration Strategy and its Industrial Strategy, with all three forming important components of the European Green Deal, which aims to bring about climate neutrality in the European Union by 2050.

The document is an ambitious first step in the development of a European hydrogen economy and contains a number of targets, investment goals, and regulatory mechanisms by which it may be stimulated and encouraged. Individual Member States, such as France, Germany, and the Netherlands, have also published national hydrogen strategies, illustrative of a growing interest in and desire to accelerate the development of a mature, integrated hydrogen industry.

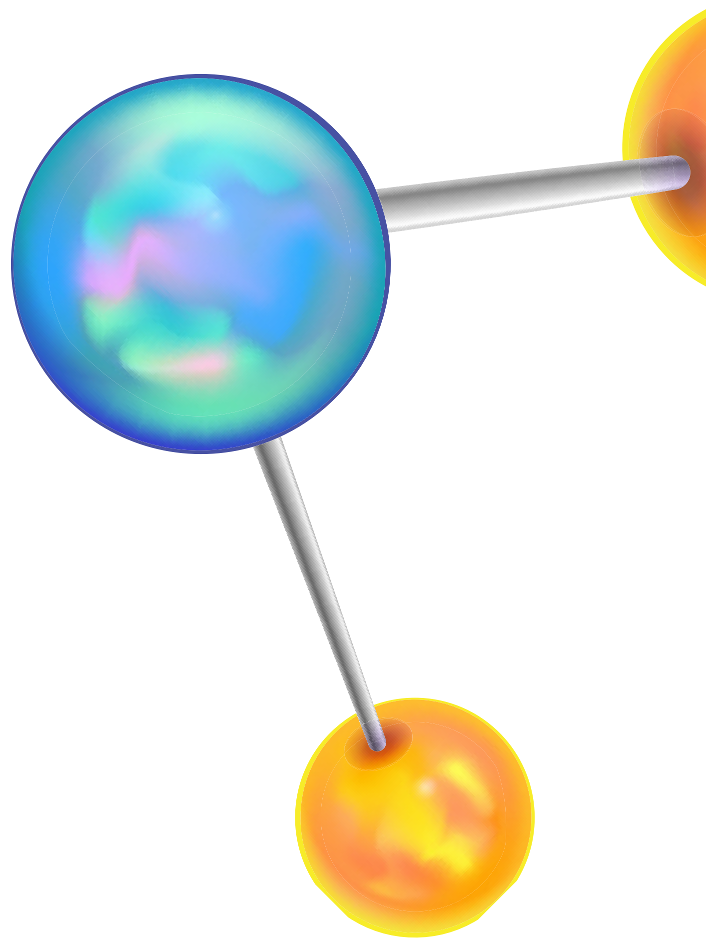
This broad-based interest in hydrogen is a result of an ever-increasing recognition of the role that the fuel could play in the transition towards a decarbonised energy system, amplified by the falling cost of certain production technologies. The attraction of hydrogen, the combustion of which results in no emissions, lies in its potential ability to facilitate the decarbonisation a number of sectors and sub-sectors, in industry, transport, and heating, that would otherwise prove difficult and expensive to decarbonise via electrification. It has also been argued that the production of hydrogen using excess renewable generation is a means by which renewable capacity can be integrated into the power system with greater ease and at lower cost. Finally, an increase in the use of hydrogen offers a means by which national energy systems are able to diversify their fuel base and may allow for the strengthening of energy security, if produced domestically.

At the present the production of hydrogen itself, rather than its combustion in use, is a highly carbon-intensive process, responsible for around 830 million tonnes of carbon dioxide emissions on an annual basis, an amount greater than that emitted yearly by Germany. Therefore, the twin challenges for policymakers are to stimulate a significant increase in the production and use of hydrogen while ensuring that an ever-growing proportion of the market is accounted for by 'clean' hydrogen, produced in a climate neutral manner. The latter can be achieved by using low-carbon electricity, such as that generated by nuclear power, hydropower, and renewables, to produce hydrogen via the electrolysis method, which entails the decomposition of water into hydrogen and oxygen using an electric current.

However, the European Hydrogen Strategy makes clear that it regards the long-term future of the European hydrogen economy as one entirely based on hydrogen produced using renewable power only, thereby excluding nuclear power from a lasting role in the market. Certainly, the Strategy acknowledges that other forms of low-carbon hydrogen production will be required in the short- and medium-term to facilitate early-stage market development, and so grants them access to a number of the support mechanisms and policy incentives as renewable hydrogen, but does not provide any long-term certainty to potential producers and excludes the other forms from its major targets.

This technological prejudice is to the detriment of the Strategy on a number of fronts. As noted, the Strategy acknowledges the importance of non-renewable yet still low-carbon hydrogen production in the near-term yet, by granting it no long-term role in European Strategy, greatly weakens the commercial incentive for nuclear and hydropower producers to invest not only in production technologies (electrolysers) but also the broader hydrogen network infrastructure (including storage and distribution/transmission channels) and workforce skills development that are required. Indeed, nuclear power companies are instead reliant on the actions and decisions of individual Governments, as can be seen in the differing approaches of the national strategies of France and Germany, with the former pushing ahead with nuclear-produced hydrogen, while the latter relies up the import of hydrogen produced elsewhere in Europe and its neighbouring regions.

EXECUTIVE SUMMARY



Moreover, the production of hydrogen using nuclear power rather than intermittent renewable energy has a number of general advantages, not in the least that the former is able to supply electrolysers at a far higher capacity factor, allowing greater operational efficiency, and to facilitate continuous production of hydrogen that is essential for its industrial applications.

As this report demonstrates, per unit of installed capacity of electrolyser, nuclear power is able to produce over 5 and over 2 times as much low-carbon hydrogen as solar and wind power respectively. Moreover, and again demonstrated in this report, the land area required to produce hydrogen using nuclear power is considerably lower than that required by renewable energy sources – a hypothetical example indicates that an offshore wind farm, of a type similar to the Hornsea One installation in the UK, would require 1,400 times the surface area to produce an amount of hydrogen that could be produced by Hinkley Point C.

This report also makes clear that the significant role that nuclear power could play in the near-term development of the market. Due to the Covid-19 pandemic and the economic downturn that is has precipitated, and which is forecast to remain for some time, nuclear generation has fallen by some 3% on an annual basis. In Europe, this corresponds to more than 3 GW of spare capacity which could be used to produce 286,000 tonnes of clean hydrogen and save ten times that amount in carbon emissions compared to the dominant natural gas-based production method. This volume of hydrogen, beyond reducing carbon emissions, would help stimulate investment in the wider infrastructure upon which a liquid, integrated European clean hydrogen economy could begin to evolve and flourish. Therefore, this report ends with a call for the valuable role of nuclear-produced hydrogen to be acknowledged by policy and for European and national strategies to adopt a technologically neutral, yet firmly low-carbon based, approach to their hydrogen strategies.

01 Hydrogen Overview

Hydrogen is not an energy source but an energy carrier and so is similar to electricity in a number of ways, both can be produced by using various technologies and both can be used in multiple applications.

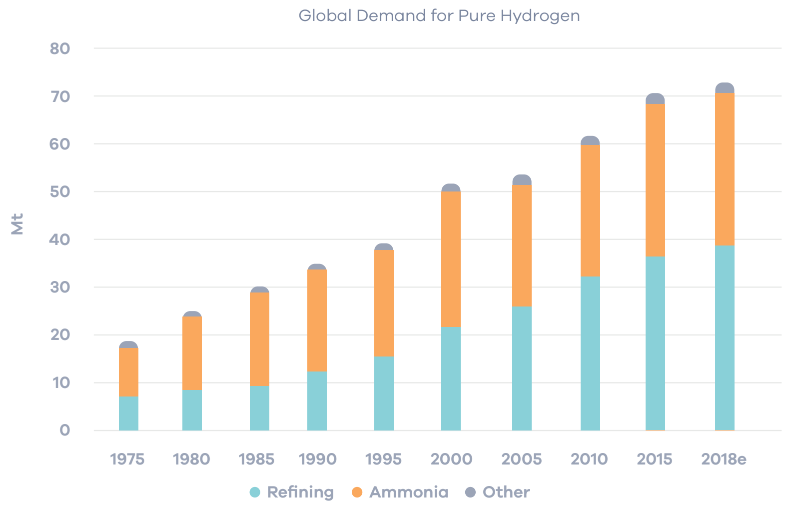
The use of either hydrogen or electricity does not result in the emission of any greenhouse gases – the use of hydrogen in a fuel cell results in emissions of nothing but water – but both can have a high upstream carbon intensity if produced using fossil fuels. This drawback can be avoided if fossil fuel plants are equipped with carbon capture, use and storage (CCUS) or if the initial energy source in the production process is a low-carbon one, such as nuclear power and renewables.

The critical difference between electricity and hydrogen is that while the former is composed solely of electrons, the latter is a chemical energy that is composed of molecules. The distinction is of the utmost significance due to the fact that molecular energy is storable and can be transported in stable manner, as fossil fuels are transported on a global basis in the present day. Moreover, the molecular nature of hydrogen allows for its combination with other elements to make hydrogen-based fuels that can be used in industry. In terms of energy content, the world market for molecular energy, dominated by oil, natural gas, and coal, is eight times larger than the electricity market. Therefore, and notwithstanding the expected trend towards greater electrification as a means by which to decarbonise certain energy processes, it is clear that low-carbon hydrogen will be an essential component of the energy transition.

A. Production

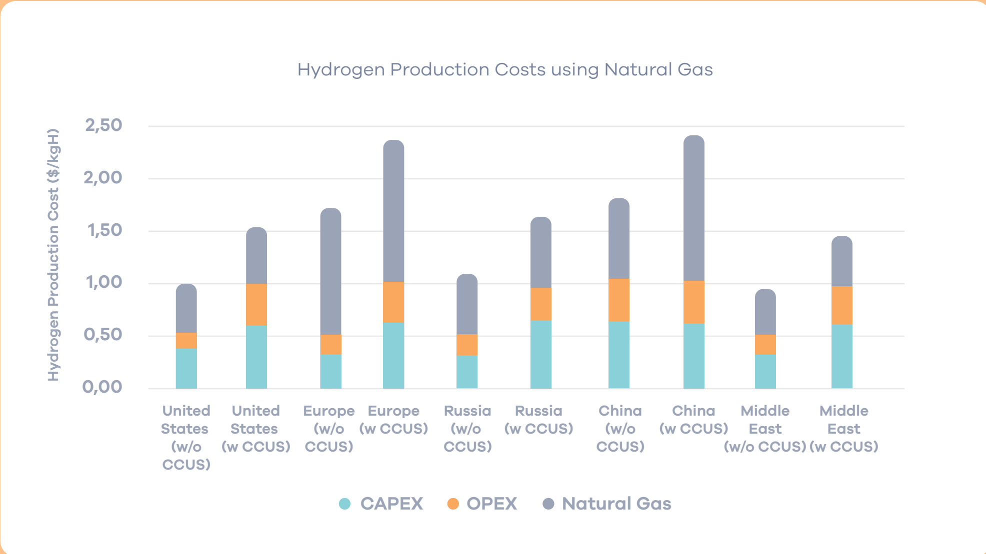
There were 73.9 Mt of dedicated hydrogen – hydrogen used in its pure form – produced in 2018, according to the International Energy Agency (IEA), along with a further 45 Mt of hydrogen that had not been separated from other gases used in various industrial applications, such as the production of methanol and direct reduced iron steel production.

Almost all of the dedicated hydrogen that is produced in the world today is used in oil refining and the production of ammonia.



The most well-established technology for hydrogen production, accounting for 76% of total dedicated hydrogen production, is steam methane reforming (SMR) which uses natural gas as both a feedstock (in addition to water, which is used as an oxidant and a source of hydrogen) and a fuel.

Under typical operating conditions, between 30-40% of the natural gas is combusted as fuel in the process while the rest is separated into hydrogen and concentrated carbon dioxide. Today, this method consumes slightly more than 200 billion cubic metres of natural gas annual on a global basis, representing 6% of the natural gas use of the world. SMR production is also carbon-intensive and results in emissions of 10 tonnes of carbon dioxide per tonne of hydrogen, which can be reduced by up to 90% if the facility is equipped with CCUS but at a greater cost of production, as the graph from the IEA below indicates.



Of the remaining dedicated hydrogen that is produced in the world today, the majority is produced from coal, using the gasification method. Most production of this type is concentrated in China where more than 80% of the world's coal gasification plants are located and in which the method is the lowest cost option for producing hydrogen.

The process is almost twice as carbon intensive as SMR using natural gas, resulting in 19 tonnes of carbon dioxide per tonne of hydrogen, and so the addition of CCUS is required if emissions are to be lowered.

Hydrogen can also be produced from water and electricity using the technique of water electrolysis, although the method accounts for less than 0.1% of dedicated hydrogen production currently and mainly serves niche markets in which high-purity hydrogen is required. However, momentum behind electrolytic hydrogen is growing due to the expected decreases in the cost of the underlying technology and the potential role that it can play as a decarbonising agent in the energy transition (which is discussed in the section that follows). The process uses electricity to split water into hydrogen and oxygen, producing 1 kilogramme of hydrogen per 9 litres of water at efficiency rates of between approximately 60% and 80%.

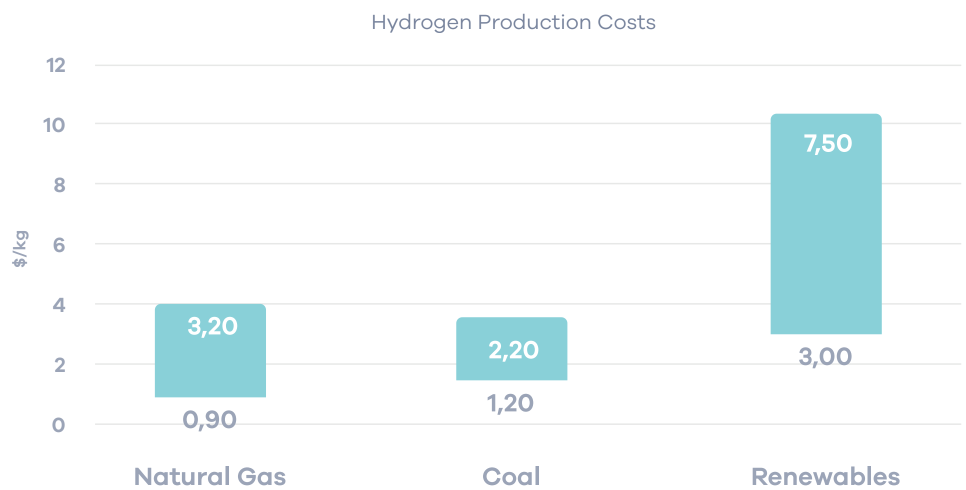
Electrolytic Hydrogen: Technology Options

Alkaline Electrolysis has long been an established technology in the chemical industry and has a relatively low capital cost compared to other methods (ranging from $500 to $1,400 per kW today, according to the IEA) as, in addition to its status as a mature, commercialised type of electrolyser, it does not require any precious metals. It is able to operate from a minimum load of 10% to full design capacity.

Proton Exchange Membrane (PEM) Electrolysis was first introduced in the 1960s by General Electric to overcome the drawbacks, principally related to operating efficiency, of alkaline electrolysis. PEM electrolysers are also able to operate more effectively in part-load and overload conditions than alkaline electrolysers and can operate under highly dynamic power supply conditions as well, which has stimulated interest in integrating them with renewables as a means by which to balance the electricity market. However, the infancy of the technology relative to alkaline electrolysers as well as its use of precious metals as catalyst materials means that it has a higher capital cost ($1,100 to $1,800 per kW).

Solid Oxide Electrolysis Cell (SOEC) Electrolysis has not yet been commercialised and so has a capital cost that is the highest of the three ($2,800 to $5,600 per kW). SOEC electrolysers use steam as the catalyst – and so operate at high temperature, leading to higher efficiency but a faster rate of material degradation – and so require a heat source. Unlike either alkaline or PEM electrolysers, SOEC electrolysers can also be utilised as a fuel cell, able to reverse the electrolysis process and convert hydrogen into electricity.

The cost of electrolytic hydrogen is determined in the main by the capital cost (which vary according to the electrolyser technology used as well as the production scale of the facility), the input electricity price, the conversion efficiency achieved, and the annual load. As the operating hours of an electrolyser increase, the effect of the capital cost on the final output cost – the levelised cost of hydrogen production – declines while the impact of the electricity price increases. Therefore, the optimal operating conditions are characterised by a high and consistent load factor (provided by high and consistent electricity supply) and low electricity prices. The relative cost of hydrogen produced using renewable-backed electrolysis is high compared to the dominant production methods of today, as the IEA graph below illustrates[1], due to electrolyser capital costs and the relatively low capacity factor offered by renewables compared to baseload, dispatchable power sources.



[1] The IEA report (The Future of Hydrogen, 2019) does not explicitly model the production cost of hydrogen using nuclear power, but it will be discussed in detail in Section Three.

The carbon intensity of hydrogen produced via the electrolysis method is determined by the carbon intensity of the electricity source and so electrolysers are able to produce low-carbon hydrogen.

This can be achieved by grid-connected electrolysers if the wider power system is itself low-carbon or by electrolysers paired to a dedicated source of low-carbon electricity, such as nuclear power or renewables. The dedicated generator method would allow for greater operational flexibility as production can be switched between electricity and hydrogen in response to system needs and market forces. It has also been proposed as a means by which the overproduction of renewable electricity that can occur at times of high generation can be put to a valuable use, thereby limiting the occasions of enforced curtailment.

B. Potential as a Decarbonising Agent

The contribution that low-carbon hydrogen can make to the decarbonisation of the energy system is twofold. Firstly, it can replace the carbon-intensive hydrogen that is currently being consumed by oil refiners, ammonia producers, and other industrial users.

At present, the global production of hydrogen results in the emission of roughly 830 million tonnes of carbon dioxide per year, greater than the 800 million tonnes of carbon dioxide produced by Germany in 2018[2]. Secondly, it can be employed in new and novel applications as a means by which to replace current fossil fuel use, especially in those sectors and sub-sectors in which electrification is either unfeasible or uneconomic, and so deliver wider decarbonisation (as well as fuel diversification).

Enveloping and adding to both of the above is the idea that greater demand for low-carbon hydrogen also eases the integration of greater renewable capacity into the electricity grid by removing the constraint of renewable overproduction and the associated cost of curtailment and suppressed prices (that result from the self-correlation of weather-dependent generators) and allowing for the economic conversion of low-carbon electrons into valuable low-carbon molecules that can be stored and transported. The long-term (over ranges of days or weeks and longer) storage of energy as hydrogen – as opposed to short-term during which time batteries are preferable – represents a feasible means by which the seasonal variations in renewable generation could be balanced.

[2] https://ec.europa.eu/jrc/en/publication/fossil-co2-emissions-all-world-countries-2018-report

i. Industrial Feedstocks

As discussed above, the dominant use of hydrogen today is in industrial applications, if the production of both dedicated and mixed hydrogen are combined then oil refining accounts for one-third of the total and ammonia production for slightly less than 30%, and it is almost exclusively produced using fossil fuels.

Hydrogen demand from these specific uses is forecast to rise 7% and 31% respectively by 2030, although the former is heavily dependent on the future evolution of oil demand. In the longer term, and contingent upon certain technological challenges being resolved and policy support, the production of steel (via the direct reduction of iron method) and high-temperate heat could also become significant sources of hydrogen demand.

Given the high level of existing industrial demand for hydrogen, a progressive switching from hydrogen produced using fossil fuels to hydrogen produced using low-carbon energy is a clear route to decarbonisation. Moreover, there is no other or competing low-carbon solution for almost all the applications of hydrogen as an industrial feedstock and so policy that acts to accelerate switching, such as the use of minimum low-carbon threshold targets, could prove to be particularly effective in generating demand for low-carbon hydrogen, which in turn will be critical in reducing the cost premium that currently disadvantages low-carbon hydrogen as production economies will be achieved.

ii. Mobility

Today, the transport sector accounts for over one-fifth of total global carbon dioxide emissions and is forecast to rise by 35% under the IEA's reference scenario.

The average volume of emissions per kilometre travelled will have to decrease by in excess of 70% if the same organisation's two-degree scenario is to be met. The greater deployment of hydrogen fuel cell electric vehicles (FCEVs), in tandem with the deployment of hydrogen refuelling stations (HRSs) are one means by which the sector can start to decarbonise.

However, and unlike in the industrial feedstock market, FCEVs face a direct low-carbon challenge in the form of battery electric vehicles (BEVs). Thus far, BEVs have outsold FCEVs by a considerable margin, the global FCEV fleet slightly exceeded 25,000 by the end of 2019 whereas Tesla, the American BEV company, delivered over 110,000 units in the fourth quarter of 2019 alone[3]. The low production of FCEVs is itself a drag on the prospects of future FCEV demand, as the cost of fuel cells remains high while production is low and there is little commercial incentive to install the required network of HRSs while their utilisation will also remain low.

[3] https://ir.tesla.com/press-release/tesla-q4-2019-vehicle-production-deliveries#:~:text=In%202019%2C%20we%20delivered%20approximately,with%20our%20full%20year%20guidance.

However, there are a number of niche applications in which FCEVs may be preferable to BEVs due to their faster refuelling times and longer distance ranges.

These are found in captive fleet or haulage sub-sectors of transport in which longer distances are required and in which a single central depot can serve as an HRS in order to maximise utilisation and so improve operating efficiency; examples include: heavy-duty trucks or hauliers, long-distance coaches, and even forklift fleets[4]. Moreover, hydrogen-powered trains are preferable to electric trains in areas in which the absence of a catenary line increases the cost of electrification – the first fuel cell train was launched in Germany in 2018[5]. Finally, hydrogen may also play a role in the decarbonisation of the aviation and shipping sub-sectors, which together account for roughly 5% of total global emissions, but several technical and commercial obstacles must first be overcome and so this remains a long-term possibility.

iii. Building Heat

Buildings were responsible (after the reallocation of electricity and heat) for slightly less than 30% of global emissions in 2018 (8.87 Gt in total[6]) and represented 30% of global final energy use, of which close to three-quarters was used for space heating, producing hot water, and cooking.

The diversity of the global building stock implies that its decarbonisation will likely rely on a number of alternative low-carbon technologies, including electrification, the use of fuel cells, and district heating, and the use gaseous hydrogen is best-suited to areas in which a natural gas heating infrastructure and network already exists and can be leveraged to operate either partially or fully using hydrogen.

Partial use of the existing natural network refers to blending, in which hydrogen is blended into the network in order to reduce the overall carbon content of the heat stream. The upper limit on the blending ratio is determined by the reduced energy density of hydrogen compared to natural gas on a volumetric basis and required adaption of end-use equipment, such as boilers and stoves. Hydrogen blending ratios of up to 20% have been achieved in small-scale projects in both the United Kingdom[7] and France[8]. However, hydrogen blending is itself unlikely to prove to be a pathway to the complete decarbonisation of building heat, although if minimum thresholds for low-carbon hydrogen were mandated by policy it would represent a significant short- and medium-term demand offtake potential.

[4] https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
[5] https://www.theguardian.com/environment/2018/sep/17/germany-launches-worlds-first-hydrogen-powered-train
[6] https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2018
[7] https://www.itm-power.com/news/hydeploy-uk-gas-grid-injection-of-hydrogen-in-full-operation
[8] https://www.engie.com/en/businesses/gas/hydrogen/power-to-gas/the-grhyd-demonstration-project#:~:text=This%20ambitious%20project%20aims%20to,heating%2C%20water%20heating%20and%20fuel.&text=The%20project%20was%20launched%20in%202014.

02 European Policy Frameworks

While the potential of hydrogen to facilitate widespread decarbonisation, or at least lower emissions, across a range of sectors is well understood, the market for hydrogen remains in its infancy, dominated by industrial consumers. Therefore, the twin challenges that policymakers are faced by are that of expanding the market, by stimulating both the production and the consumption of hydrogen, and that of increasing the share of the market that is met by decarbonised hydrogen without compromising competitiveness.

A. The European Hydrogen Strategy

The European Commission's hydrogen strategy, A hydrogen strategy for a climate-neutral Europe[9], published in July 2020, identifies hydrogen as a key tool in achieving the decarbonised energy transition of the region and forms part of the broader European Green Deal action plan.

It sets out a number of classifications for hydrogen that relate to the manner in which it was produced, contains targets for the installation of electrolyser capacity, and outlines the regulatory arrangements and required investment that will be required to accelerate the development of the hydrogen market.

Notably, the Strategy makes clear that hydrogen produced using renewable electricity is the desired long-term outcome and that low-carbon hydrogen is viewed as an interim option only, insofar as its production can stimulate market development in the short- and medium-term. This is reflected in the treatment of renewable hydrogen relative to low-carbon hydrogen, with only the former included in capacity targets and eligible for regulatory and policy support despite the fact that hydrogen produced using nuclear power, which is not considered renewable, has zero emissions.

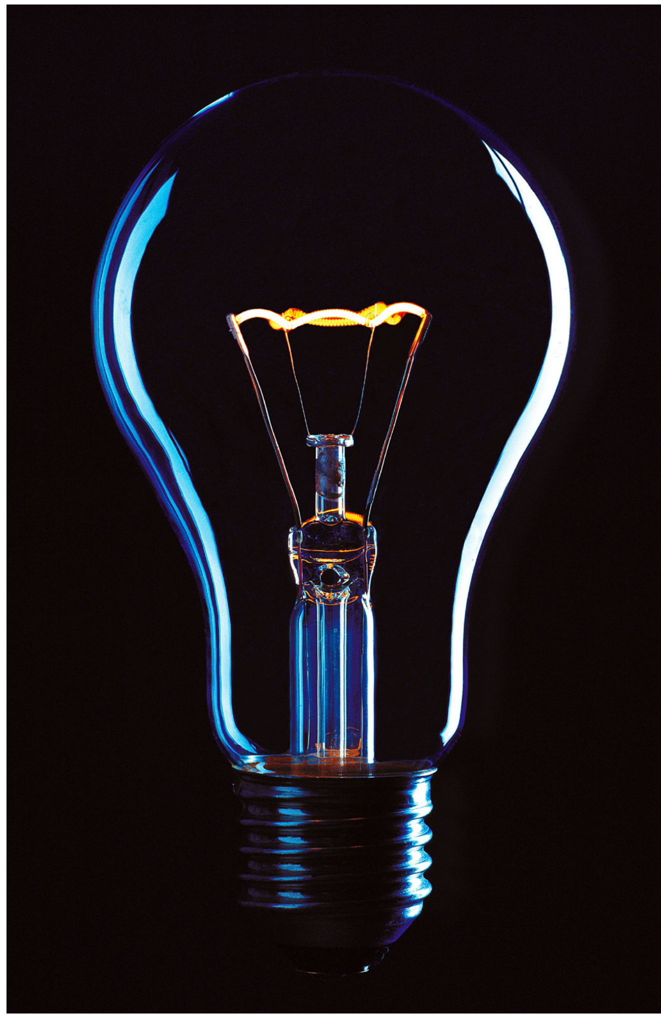
[9] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

i. Classifications

The terminology used by Strategy differs from the usual colour-based descriptions of hydrogen ('grey', 'blue', 'green', etc.) and is summarised in the table below.

It should be explicitly noted that 'low-carbon hydrogen' can be produced using electricity from any source, regardless of carbon intensity, and so includes power generation using fossil fuels.

Electricity-based Hydrogen
refers to hydrogen produced via the electrolysis of water, regardless of the electricity source.
Renewable Hydrogen
refers to hydrogen that is produced via the electrolysis of water using the electricity that is produced using renewable sources.
Fossil-based Hydrogen
refers to hydrogen that is produced through a variety of processes using fossil fuels as feedstock – a secondary distinction is made between 'fossil-based hydrogen' and 'fossil-based hydrogen with carbon capture'.
Low-Carbon Hydrogen
refers to hydrogen that is produced either using fossil fuels with carbon capture or electricity-based hydrogen.
Hydrogen-Derived Synthetic Fuels
refers to a range of gaseous and liquid fuels based on hydrogen and carbon – synthetic fuels are only considered renewable if the hydrogen component is renewable.



The Strategy notes that neither renewable hydrogen nor low-carbon hydrogen with carbon capture can compete with fossil fuel hydrogen on price, with estimated costs of €2.5-5.5/kg and €2.00/kg respectively compared to €1.50/kg and that a carbon price between €55-90 per tonne of carbon dioxide would be required to eradicate the cost disparity.

ii. Targets

The Strategy, as discussed, makes clear that the priority for the European Union is to develop renewable hydrogen but it acknowledges that in the short- and medium-term other forms of low-carbon will be required in order to reduce the aggregate carbon intensity of hydrogen production and to support the wider consumption of hydrogen by end-users.

Given the dominance of natural gas in the current supply of hydrogen, this suggests that large-scale carbon capture projects will have to be developed during the next decade, yet the European Commission is yet to deliver a policy framework for CCUS and so private investor sentiment remains wary[10].

The delivery of the Strategy, A roadmap for EU, is divided into three stages, each with their own targets and goals, and is summarised in the table below. It should be noted that 2.5 gigawatts (GW) of renewable electrolyser capacity is approximately the equivalent of 1 billion cubic metres (bcm) of natural gas and that natural gas consumption in the European Union amounted to 474 bcm in 2018[11].

Target	Renewable Hydrogen Electrolyser Capacity (GW)	Production of Renewable Hydrogen (Tonnes)
Phase One: 2020-2024	**6**	**1,000,000**

In this phase, the focus is on decarbonising existing hydrogen productions, the primary source of which is the industrial sector, and to increase the uptake of hydrogen in new end-use applications in other industrial processes and selected haulage fleets. The manufacturer of electrolysers will need to scale-up, from c.10 MW today to up to 100 MW. The electrolysers will be installed in existing demand centres (or industrial clusters) or to support a growing network of HRSs and ideally will be powered directly by local renewable energy sources. Transmission and distribution infrastructure will remain limited as demand is met by on-site or local production, although limited hydrogen blending may occur. The policy focus will be on laying down a regulatory framework that supports market development and efforts to bridge the cost-gap between conventional and renewable hydrogen.

[10] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/09/Insight-73-EU-Hydrogen-Vision-regulatory-opportunities-and-challenges.pdf
[11] https://ec.europa.eu/energy/sites/ener/files/quarterly_report_on_european_gas_markets_q4_2018.pdf

Target	Renewable Hydrogen Electrolyser Capacity (GW)	Production of Renewable Hydrogen (Tonnes)
Phase Two: 2025-2030	**40**	**10,000,000**

In this phase, hydrogen is integrated into the whole energy system as renewable hydrogen becomes cost-competitive with other forms of hydrogen production, although demand-side policies will be required to drive uptake across new hydrogen applications. During this phase, hydrogen will start to be used to balance renewable electricity and as a long-term energy storage vector. The equipping of fossil fuel using hydrogen producers with carbon capture should continue, in line with the 2030 emission target. The use of hydrogen will expand beyond industrial clusters to encompass isolated and/or regional areas (so called 'hydrogen valleys') where production of hydrogen uses decentralised renewable energy sources and limited local distribution. At this stage, the transportation of hydrogen over longer distances will emerge as a possibility and a hydrogen 'back-bone' will need to be planned and developed, potentially repurposing part of the natural gas grid infrastructure. International trade will also develop, with neighbouring countries in Eastern Europe and the Southern and Eastern Mediterranean identified as likely partners. By the end of this phase, policy should deliver an open and competitive European hydrogen market, with international trade and efficient allocation of hydrogen production.

Target	Renewable Hydrogen Electrolyser Capacity (GW)	Production of Renewable Hydrogen (Tonnes)
Phase Three: 2031-2050	**500***	**not stated**

In this phase, hydrogen should reach maturity and be deployed across all sectors in which other decarbonisation pathways are unfeasible and/or uneconomic, with aviation and shipping identified as potential candidates. The production of renewable energy required to produce the hydrogen required will necessitate an increase of the former by 25%.

* The figure of 500 GW of renewable electrolyser capacity in Phase Three is not found in the body of the Strategy but is located in Footnote 35, in which it is stated that the estimated figure for the investment required to deliver the Strategy is based upon a 2050 estimate of 500 GW of renewable electrolyser capacity.

The rapid expansion of renewable electrolyser capacity will require considerable investment, the Strategy estimates that between now and 2030, investments in electrolysers will amount to €24-42 billion, rising to €180-470 billion by 2050, and a further €220-340 billion of investments in solar and wind generation capacity (to connect between 80 and 120 GW) will be required. These figures to not include the investment required to adapt end-use applications to hydrogen, such as the installation of HRSs.

iii. Support Policies and Schemes

To stimulate the production of renewable and low-carbon hydrogen and so bring about decreases in the carbon intensity of its production, the Strategy states the Commission will work to introduce a low-carbon standard for hydrogen producers that is based on lifecycle emissions, potentially calculated relative to the benchmark of the existing Emissions Trading System (ETS).

The monitoring function of the ETS may also be used to establish a certification process for renewable and low-carbon hydrogen that mimics the Guarantees of Origin (GOs) and sustainability certificates brought in by the Renewable Energy Directive.

Furthermore, as the Strategy envisages that renewable and low-carbon hydrogen production will require targeted support until cost parity with conventional hydrogen is achieved. The policy suggested in the Strategy is to create carbon contracts for difference (CCfDs) that would pay investors in renewable and low-carbon hydrogen the difference between strike price of carbon dioxide in the contract and actual price of carbon dioxide as reflected in the ETS. The effect of such a policy would be to reduce or eliminate the cost gap borne by renewable and low-carbon hydrogen producers.

In order to scale up specific demand for renewable hydrogen, the Strategy suggests that the European Commission will consider a variety of possible incentive instruments, including the possibility of minimum thresholds or quotas of renewable hydrogen (and its derivatives) in specific end-use sectors. As discussed above, this course of action would be particularly well suited to existing industrial applications, as substantial demand already exists and so the gradual transition to a greater share of renewable hydrogen can start immediately.

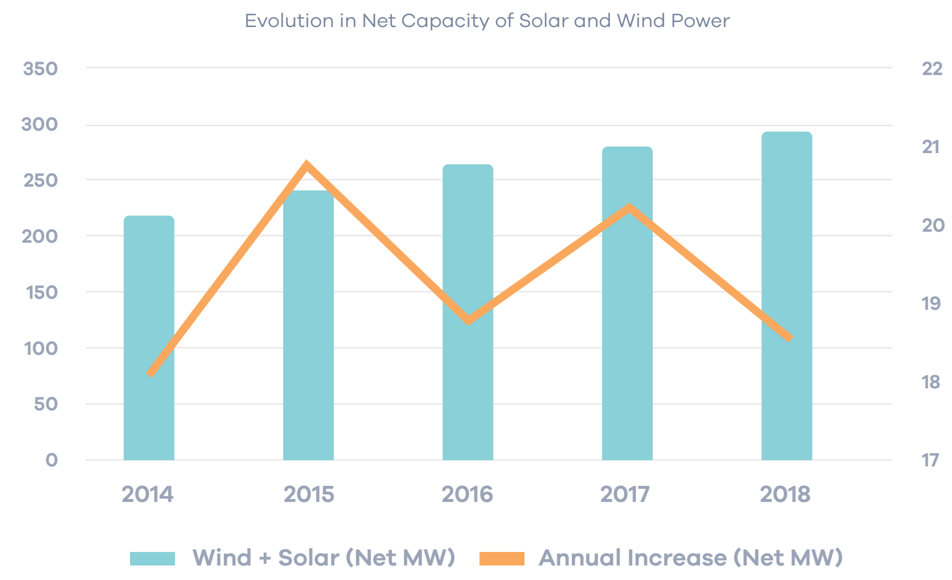
iv. Challenges

One criticism of the Strategy, as noted by the Oxford Institute of Energy Studies in EU Hydrogen Vision: Regulatory Opportunities and Challenges, is that it assumes that the development of a broad hydrogen market and its related infrastructure will develop in a manner that is compatible with the regulatory framework that currently guide the natural gas market.

In particular, it assumes that the coordination required to develop hydrogen production, demand, and infrastructure can be achieved in an unbundled, post-vertical market regime. As a result, the incrementality or marginal nature of the support schemes and policies outlined in the strategy may prove to be insufficient, which would leave Europe stranded in the transition phase of its hydrogen development, in which natural gas continues to dominate hydrogen supply and significant investments in CCUS technologies and large-scale storage facilities (of which there are currently none in the European Union while two are operational in Norway) are required[12].

Another criticism of the Strategy is its focus on renewable hydrogen and related limited commitment to low-carbon hydrogen that is produced using low-carbon electricity, such as nuclear power. If the forecast investments in renewable hydrogen (including electrolysers and renewable generation capacity) are realised at their maximum the total figure stands at €382 billion by 2030 while the forecasted figure for investment in low-carbon fossil-based hydrogen is expected to range between €3 and €18 billion for low-carbon hydrogen produced using fossil fuels. There is no estimate for investment in low-carbon hydrogen produced using low-carbon electricity.

This is flawed for two reasons, the first of which is that including nuclear-produced hydrogen would bring multiple benefits to the development of a European hydrogen system and will be explored in Section Three. The second is that it necessitates a sizeable increase in renewable generation in a context in which both gross electricity demand and the share of renewable electricity in the electricity mix are already forecast to rise. The European Commission's Energy System Integration Strategy[13] projects that electricity demand as a share of final energy consumption will rise from 23% today to around 30% in 2030 and to 50% in 2050 (with all scenarios in the related analysis also indicating a rise in gross electricity generation[14]) and that the share of total electricity accounted for by renewables will double to 55-60% by 2030 and rise to 84% by 2050. As a result, there is already considerable pressure placed on the expansion of renewable capacity (in addition to the implied land mass required by such an expansion) that is exacerbated by the exclusion of nuclear- and hydro-produced hydrogen from the long-term goals of the Strategy. For example, the Strategy aim of installing 80 to 120 GW of wind and solar power dedicated to hydrogen production by 2030 would account for all the wind and solar net capacity additions achieved between 2013/2015 and 2018[15] alone.



[12] https://co2re.co/FacilityData
[13] https://ec.europa.eu/energy/sites/ener/files/energy_system_integration_strategy_.pdf
[14] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf
[15] https://ec.europa.eu/eurostat/databrowser/view/NRG_INF_EPCRW__custom_187723/default/table?lang=en

B. National Hydrogen Strategies Compared: France and Germany

The interest in hydrogen reflected in the Strategy has been mirrored at the national level in Europe too, five European Union and European Economic Area had released national hydrogen plans by early September 2020 (France, Germany, the Netherlands, Portugal, and Norway) with a number of others expected to follow[16].

In this section of the report, the national strategies of France and Germany will be compared as a means by which to identify some of the specific advantages of including nuclear-produced hydrogen in such plans, which will then be assessed at a more general level in Section Three.

i. France

In September 2020, France published its second national hydrogen strategy[17], which included a substantial raise in annual public funding compared to its first strategy (published in 2018) from €150 million to €700 million (or €7 billion in total for the period 2020-2030).

The headline target is for France to install 6.5 GW of electrolyser capacity by 2030, which is again a substantial increase relative to its first national strategy which envisaged 10-100 MW of installed capacity by 2028. The strategy also makes clear that its focus is to be on decarbonised hydrogen – that is hydrogen produced in a low-carbon manner at both the upstream and the downstream and so includes nuclear-produced hydrogen as well as renewable hydrogen – to be used for industrial and transport applications. The hydrogen industry itself will be supported by the introduction of a premium-based support mechanism, to stimulate private investment, in addition to tenders for projects along the hydrogen supply chain, including fuel cell development, as well as other research proposals. The national strategy is also supported by a number of regional initiatives.

[16] https://hydrogeneurope.eu/sites/default/files/2020-10/Clean%20Hydrogen%20Monitor%202020_0.pdf
[17] https://www.politico.eu/wp-content/uploads/2020/09/dp-hydrogren-strategy.pdf

		2023	2028	2030
Production	Electrolyser Capacity (GW)	/	/	6.5
Transport	Passenger Cars / Light Commercial Cars (LCVs)	5,000	20,000 – 50,000	/
	Heavy Duty Vehicles (HDVs)	200	800 – 2,000	/
	Hydrogen Refuelling Stations (HRS)	1,000	400 – 1,000	/
Industry	Decarbonised Hydrogen Share (%)	10	20 – 40	/

ii. Germany

Germany released its national hydrogen strategy[18] in June 2020, with targets for installed renewable electrolyser capacity of 5 GW by 2030 and 10 GW by 2040 (by 2035, if possible), backed by €7 billion in public funding. The strategy predicts that 90 to 110 terawatt hours (TWh) of hydrogen will be required by 2030 and makes clear that domestic production will be insufficient to meet that level of demand.

The initial 5 GW target for installed renewable electrolyser capacity is said to correspond to 14 TWh of renewable hydrogen, between 13 and 16% of the expected need, and so the strategy envisages that most of Germany's hydrogen will be imported, which is reflected in the €2 billion allocated to developing international partnerships; one such partnership has already been signed with Morocco to take advantage of its solar potential[19]. The primary sectorial focus of the strategy is in the industrial sector, although €3.6 billion of funding (with €2.1 billion available for passenger cars and light commercial cars) from the Energy and Climate Fund has been made available to hydrogen-powered vehicles until the end of 2023.

		2030	2040	2050
Production	Electrolyser Capacity (GW)	5	10	/
	Hydrogen Production (TWh)	14	/	/
	Hydrogen Demand (TWh)	90 – 110	/	/
Industry	Steelmaking Demand (TWh)	/	/	80
	Ammonia Production Demand (TWh)	/	/	22

[18] https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf
[19] https://www.moroccoworldnews.com/2020/06/305441/morocco-first-to-partner-with-germany-to-develop-green-hydrogen-sector/

iii. Comparison

The clearest distinction between the French and German strategies is the reliance of the latter on imports, whether from other European nations or neighbouring areas, while the latter is exclusively focused on French-made hydrogen.

Bruno Le Maire, the Finance and Economy Minister, was quoted by Politico[20], saying "We are helping so there will be jobs. We are helping so there will be factories. We are helping so there will be industrial relocalisation." M. Le Maire went on to say, "If we want clean hydrogen, green hydrogen, we'll needs lots of electricity and where will we produce it? In North Africa, the Middle East, then repatriate that hydrogen back to France? The carbon footprint won't be very good."

The French approach is facilitated by its acceptance of nuclear-produce hydrogen and subsequent use of its extensive nuclear fleet to produce it. M. Le Maire's conflation of 'clean' and 'green' hydrogen above (the latter is typically used to describe renewable hydrogen) illustrates that the focus of hydrogen development policy ought to be technologically neutral and instead directed by a concern about the lifecycle emissions of hydrogen production – in this regard, the environmental equivalence between renewable and nuclear-produce hydrogen is straightforward.

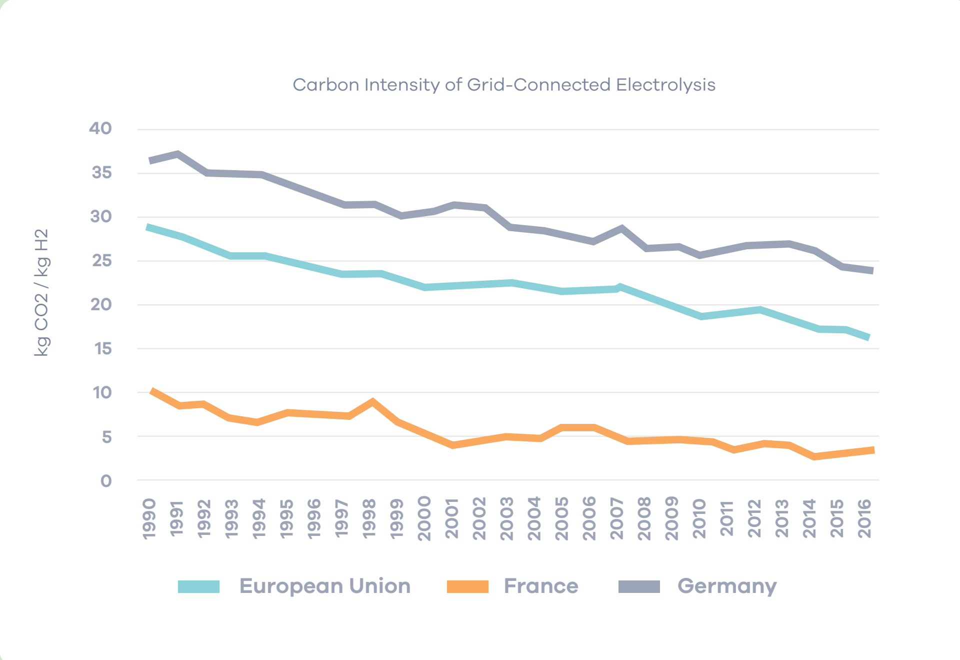
[20] https://www.politico.eu/article/france-green-hydrogen-vision/

The use of nuclear power to produce hydrogen confers a competitive advantage in that it is able to supply electrolysers with electricity for a greater proportion of the time, improving the economic efficiency of the process by allowing the electrolyser to operate with a greater capacity factor (or for a higher number of full load hours per year) than would be achievable from intermittent renewables.

As a result, the French strategy would be expected to lead to higher production per unit of installed electrolyser capacity than the German strategy, leading to a reduced need for imported and/or fossil fuel with carbon capture hydrogen.

Finally, and with the existing cost premium of renewable hydrogen in mind, it should be noted that the reliance of the German strategy on imported renewable hydrogen will further disadvantage the competitive position of renewable hydrogen due to the cost of international transportation (either by pipeline or ship, with additional costs related to the required infrastructure).

As a result, the development of the hydrogen market in Germany will either require greater support or would be expected to occur at a slower pace. Whereas the French strategy, focused as it is on domestic production, is less sensitive to such costs. Moreover, the high combined penetration of nuclear power and renewables in the French grid allows for the possibility of grid-connected electrolysis at low emissions, potentially increasing the geographical flexibility of production and allowing for the location of production in the proximity of existing demand centres. As the graph below illustrates, based on grid carbon intensity data from the European Environmental Agency[21] and an assumed electrical requirement of 55 kWh per kilogramme of hydrogen, the carbon intensity of hydrogen production using the grid is lower in France than both Germany and the European as a whole.



[21] https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5#tab-googlechartid_chart_11_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_ugeo%22%3A%5B%22European%20Union%20(current%20composition)%22%3B%22France%22%3B%22Germany%22%5D%7D%7D

03 The Contribution of Nuclear Power to the Development of a Hydrogen Market

While there is considerable interest in the use of thermal energy from advanced and small modular reactors designs to produce hydrogen in the future[22], the focus here shall be on the production of hydrogen via electrolysis using electricity produced by nuclear plants in the near-term.

This is not to say that the thermal production routes offered by those designs are not important but instead to highlight the valuable ways in which the latter can contribute to the pace and economy of the early-stage development of a European hydrogen market.

It should also be noted that the European Strategy is not incompatible with the production and delivery of nuclear-produced hydrogen in the short- and medium-term (as it is covered by the 'low-carbon hydrogen' definition) but the business case to invest in electrolyser capacity, as well as the longer-term associated infrastructure (related to the storage and transportation of hydrogen) and labour force development, is clearly weakened by its long-term aim of entirely renewable-based production.

As a result, the Strategy should adopt a view that is simultaneously technology neutral and low emission; as the IPCC have noted, the lifecycle emissions from nuclear and wind power are similar, and both results in fewer emissions than solar power[23].

A. Scale in Production of Clean Hydrogen

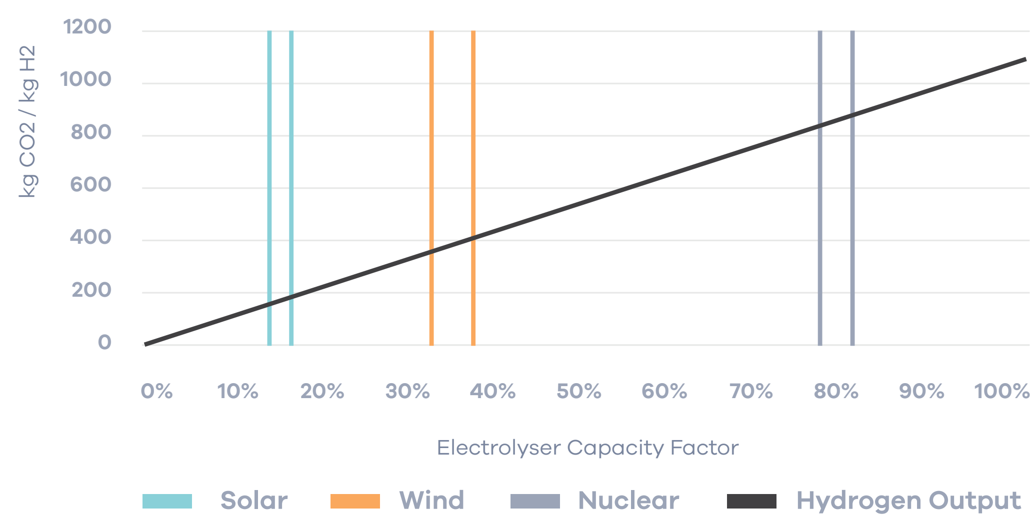
In the early stages of the development of a market there is a close relationship between supply and demand, one that is shaped by the regulatory framework and support mechanisms that have been implemented.

[22] https://energyforhumanity.org/en/resources/reports-en/report-hydrogen-from-advanced-nuclear-is-the-missing-link/
[23] https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf

In the case of clean hydrogen, for which many of its potential applications have an existing alternative fuel, the onus on production at as high a level as possible is vital if demand and end-users are to be stimulated. The scaling up of production allows for the exploitation of production economies, in turn reducing the cost premium of clean hydrogen compared to existing fuels, the adoption of clean hydrogen by larger consumers and a greater number of sub-sectors, and also a more liquid market for the trade of clean hydrogen, ensuring greater allocative efficiency.

This being the case, the focus ought to be on ensuring that available electrolyser capacity, the production capacity of which remains under 1 GW per year in Europe, is operated as effectively as possible. A simplified model, illustrated in the graph below, demonstrates the relationship between electrolyser capacity factor and total hydrogen output. The electrolyser is modelled as having a capacity of 10 MW, the size of the largest electrolyser project currently under construction in Europe, a required power input of 55 kWh per kilogram of hydrogen, and an electrical efficiency of 70%. The relative output produced using solar, wind, and nuclear power is then assessed using Europe-specific illustrative capacity factors, with solar (13-16%) and wind (33-38%) taken from analysis by Lazard (Levelized Cost of Energy Analysis, Version 14.0[24]) and nuclear (77-81%) taken from the World Nuclear Association (World Nuclear Performance Report 2018[25]).

The Impact of Capacity Factor on Electrolyser Production



The analysis shows that per MW of dedicated electrolyser capacity installed, the use of baseload nuclear power results in the production of 5.45 and 2.23 times as much clean hydrogen as the use of solar power and wind power respectively. In itself, this is not a surprising result – the relative capacity factors of different electricity generation technologies are well known – but the implication is perhaps less obvious, namely that a focus solely on renewable hydrogen in the long-run must entail a greater volume of hydrogen produced using fossil fuel with or without carbon capture (otherwise known as 'blue' and 'grey' hydrogen) in the near-term if volume sufficient to simulate market development is to be produced. This implies that carbon emissions would be higher than if nuclear-produced hydrogen was to be incentivised and provided with a long-term place in Europe's Strategy. Moreover, carbon capture technology is yet to be commercialised and widely deployed and storage facilities in Europe, as already mentioned, are restricted to two Norwegian facilities.

Another issue that relates to the differences in capacity factors is the land use requirement of different electricity generation technologies, as lower capacity densities (installed capacity per area of land) imply a greater land requirement. For example, Hornsea One, an offshore wind project sited off the coast of Yorkshire (UK), occupies 407 km² of the North Sea and has an installed capacity of 1.2 GW[26], whereas Hinckley Point C, a nuclear power plant under construction in Somerset (UK) occupies 1.75 km² of land and has a planned capacity of 3.26 GW[27]. Therefore, on a km² per installed GW of capacity basis, Hornsea One requires a surface area approximately 630 times greater than Hinckley Point C. Should the 80 to 120 GW of renewable capacity dedicated to hydrogen production targeted in the European Strategy be constructed at the same capacity density as Hornsea One, at 340 km² per GW, it would require an area of sea approximately equivalent in size to Moldova[28]. Furthermore, this land requirement would be in addition to that required by the project increase in renewable capacity used for electricity, rather than hydrogen, generation.

[24] https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/
[25] https://www.world-nuclear.org/getattachment/Our-Association/Publications/Global-trends-reports/World-Nuclear-Performance-Report/world-nuclear-performance-report-2018.pdf.aspx
[26] https://hornseaprojectone.co.uk/about-the-project#0
[27] https://www.power-technology.com/projects/hinkley-point-c-nuclear-power-station/
[28] https://en.wikipedia.org/wiki/List_of_European_countries_by_area

The combined effect of the two characteristics above – capacity factor and capacity density – is stark. On a per unit of capacity basis using nuclear power to produce clean hydrogen results in 2.23 times the volume produce, and on a per unit of land area basis it contains 630 times the installed capacity. As a result, were Hornsea One to produce the same volume of hydrogen as Hinckley Point C, assuming that both were dedicated to hydrogen production, the area covered by Hornsea One would need to be slightly in excess of 1,400 times that of Hinckley Point C at just below 2,500 km².

Finally, the volume of hydrogen generated, and the associated consumption that it enables, will have an effect on the development of the wider hydrogen infrastructure. In particular, the delivery network (encompassing storage, transmission, and distribution) and refuelling stations would be expected to experience utilisation rates in-line with market growth and so operate with greater efficiency. It ought to be noted that a sizeable proportion of current industrial demand is met via on-site production and/or use of process by-products and so has not led to the integrated delivery network that the clean hydrogen market will require.

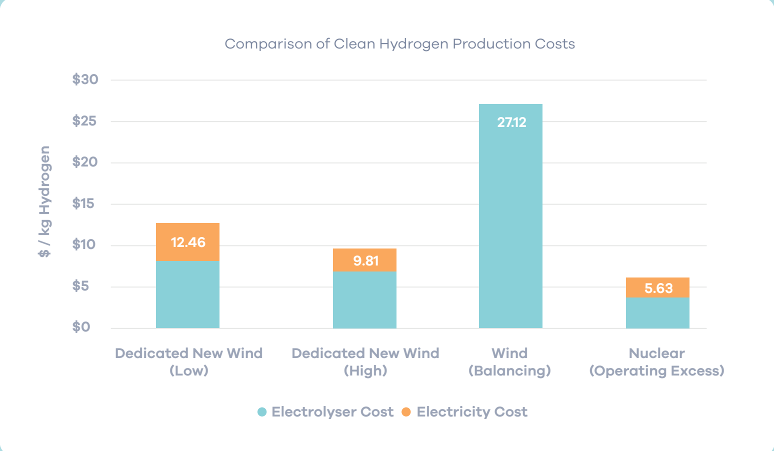
B. Production Cost of Clean Hydrogen

In addition to the volume of clean hydrogen available for consumption, the pace of market development and the amount of necessary policy support (both regulatory and financial) will also be determined by the cost disparity between clean and conventional hydrogen and at what pace it is minimised.

A failure to achieve competitiveness could also create the situation described above, in which hydrogen production is not fully able to decarbonise due the persistent presence of production using fossil fuels.

To assess the relative hydrogen production costs of different low-carbon electricity generation technologies, the capacity factor model in the previous section must be adapted to reflect the electricity cost, a significant driver of the final output cost, of each technology as well as the capital cost (per unit of installed capacity) of the electrolysis unit, taken here to be $1,400 per kWe. The electricity cost for the new installation of a dedicated wind power facility, at both high and low capacity factors, is taken from the Lazard analysis[29].

The possibility of equipping an existing wind facility with an electrolyser in order to facilitate balancing is also considered and the electricity is assumed to have zero cost due to the inability to sell at a non-zero price in an oversupplied power market. The option of equipping an existing nuclear power plant that is operating with spare capacity, as is being proposed in France[30], was also evaluated, with the electricity costs again taken from Lazard[31]. The levelised cost of hydrogen production from each technology was then calculated, illustrated in the graph below, using an assumed weighted average cost of capital of 4% across the four cases.



[29] https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/
[30] https://www.politico.eu/article/france-green-hydrogen-vision/
[31] https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/

The results of the analysis clearly demonstrate that of the four hydrogen production schemes, the use of spare capacity at an operational nuclear power plant is the lowest cost option, producing at 45%, 57%, and 21% of the low and high dedicated wind and balancing wind respectively.

The impact of the higher capacity factor of the nuclear power option is evident in a decomposition of the production cost, with 60% of the nuclear production cost accounted for by the cost of electrolyser installation as opposed to 66%, 73%, and 100% of the other options (in the same order as above).

The importance of production cost in the development of the hydrogen market is twofold. Firstly, the smaller the cost premium of clean hydrogen compared to conventional hydrogen will reduce the policy cost of increasing its use amongst existing industrial users, which, as already noted, will be a vital early-stage step in the development of demand for clean hydrogen. Secondly, the lower the production cost of clean hydrogen, the more competitive the fuel will be compared to alternative low-carbon decarbonisation agents in sectors such as transport and heating, which will in turn stimulate the demand required to facilitate further economies in its production and larger scale investments in the required hydrogen infrastructure network.

C. Current Opportunity

The Covid-19 pandemic and the economic downturn that it has precipitated led to a decline in global electricity generation of 2.6% in the first quarter of 2020 (compared to the same period in 2019), with a larger decline in nuclear power generation of 3% in the face of lower demand[32]. However, the utilisation of the spare capacity of the nuclear fleet could offer a powerful means by which to ramp up the production of hydrogen and so stimulate market development across Europe.

If the 3% decline in global power generation is assumed to be reflective of the situation in the European Union, it implies that roughly 3,300 MW of operable nuclear capacity is currently idle (based on a total capacity of 111 GW in 2018[33]) that would produce 22,500 GWh if operated at the European Union's five-year average capacity factor of 77%. If used to produce hydrogen, using the same electrolyser performance parameters as throughout this section, this amount of electricity could be used to produce 286,000 tonnes of clean hydrogen, an amount that results in the emission of 2,860,000 tonnes of carbon dioxide if produced using natural gas without carbon capture, as is currently the prevailing method. As has been demonstrated above, clean hydrogen produced in this manner – using excess capacity form already constructed and operating nuclear power plants – would be cheaper than hydrogen produced using new, dedicated renewable plants.

While the scale of this proposal is unlikely to be achieved before the end of 2020, as the electrolyser production capacity in Europe remains below 1 GW, the depressive effect of Covid and economic slowdown is unlikely to disappear by the end of 2020 and so could be pursued in the following years.

[32] https://www.iea.org/reports/global-energy-review-2020/electricity#abstract
[33] https://ec.europa.eu/eurostat/databrowser/view/NRG_INF_EPC__custom_198653/default/table?lang=en

04 Conclusion

Hydrogen has been rightly identified as a vital tool in the necessary decarbonisation of our energy systems. It offers a means by which a number of sectors can eliminate their emissions, from a variety of industrial processes to certain forms transport as well as heating.

The versatility provided by the option to produce hydrogen is also a manner by which a greater capacity of renewables may be integrated into our electricity grids, providing an economic alternative to curtailment during overproduction as well as a form of long-term energy storage to mitigate the seasonal fluctuations in weather-dependent generation. However, the substantial potential of hydrogen as a decarbonising agent will only be realised if its production at mass scale can be achieved in a way compatible with the need to sharply decrease carbon emissions.

In Europe, at the level of the European Union as well as a number of nations, including Germany, policies to develop the market for hydrogen have focused their long-term sights on renewable hydrogen, which is produced via electrolysis using electricity produced by renewables. This ignores the role that other low-carbon electricity generation technologies, such as nuclear power, can play in not only stimulating production and demand in the near-term but also the advantages of their inclusion in policymaking in the long-term. As the national hydrogen strategy of France demonstrates, the inclusion of nuclear-produced hydrogen reduces the reliance on imported hydrogen, allowing for the avoidance of transport costs as well as contributing to energy security, and contributes to wider industrial strategy.

This report has further explored the benefit of a policy commitment to nuclear-produced hydrogen. It has shown that nuclear plants are able to provide the hydrogen market with greater scale in production than are renewables and so provide greater stimulus to potential end-users as well as the development of an integrated hydrogen network. It has also made clear the ramifications of reliance on renewable hydrogen in relation to land requirements. Finally, it has demonstrated that in the near-term, using nuclear power to produce hydrogen is likely to result in a cost advantage compared to using renewables, which is another important determinant of early- and medium- stage market development.

Annex: Hydrogen Strategies and Projects of Nuclear Companies

A. Électricité de France (EDF)

i. Strategy

EDF has been exploring hydrogen for some time now, particularly within Eifer, a laboratory of EDF and the Karlsruhe Institute of Technology in Germany. In 2018, EDF acquired a 21.7% stake in McPhy, a manufacturer of electrolysers, committed to the production of low-carbon hydrogen[34]. The two firms also created a partnership, in an attempt to deliver synergies between the technological expertise of McPhy and EDF's knowledge of power systems and the production of low-carbon electricity.

In 2019, EDF published an R&D paper, titled the White Paper on Low Carbon Hydrogen[35]. Following its publication, EDF announced the launch of a new subsidiary business, Hynamics, which offers turnkey solutions for the generation and distribution of carbon-free hydrogen using electrolysis for industrial and mobility applications[36]. At the end of March 2019, Hynamics, had identified and began to work on some 40 target projects in France, Belgium, Germany and the UK[37].

ii. Technologies

Both Hynamics and McPhy produce hydrogen via water electrolysis using electrolysers, a technology that does not emit CO2, as long as the electricity used itself comes from low-carbon production methods. In April 2018, McPhy presented a modular electrolysis system capable of scaling from 4 MWe to over 100 MWe, capacble of producing 8.5 tonnes of hydrogen per day from a 20 MWe continuous input. In April 2019, McPhy launched 'Augmented McFilling', a software designed to increase the operating efficiency of hydrogen refuelling stations[38].

iii. Projects

EDF along with its partners (European Institute for Energy Research (EIFER), Atkins and Lancaster University) is assessing plans for hydrogen production powered by its fleet of UK nuclear plants, including Hinkley Point C, which is currently under construction, and the proposed plant at Sizewell C. A feasibility assessment on the viability of low-carbon production using electrolysis at Heysham Power Station in the UK was also conducted[39]. The assessment outlined an initial 2 MW system, comprising a 1 MW alkaline electrolyser and 1 MW proton exchange membrane (PEM) electrolyser, capable of producing up to 800 kg of hydrogen per day. The company estimates that a future electrolyser capacity of about 550MW across its fleet could produce about 220,000kg of hydrogen per day by 2035, with a levelised cost of hydrogen as low as £1.89/kg ($2.44/kg).

EDF leads the Moorside Clean Energy Hub in Cumbria in North West England, which has released a proposal for a group of nuclear projects in the area, including a new 3.2 GW EPR power station, small modular reactors and advanced modular reactors. The Hub is also exploring the provision of clean heat to industry as well as the possibility of becoming a centre of green hydrogen production for transport and industry[40].

[34] https://mcphy.com/en/press-releases/edf-and-mcphy-have-entered-into-a-partnership-agreement/
[35] https://www.edf.fr/groupe-edf/qui-sommes-nous/activites/notre-communaute-scientifique/l-hydrogene-decarbone-un-defi-pour-la-transition-energetique
[36] https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/all-press-releases/edf-launches-hynamics-a-subsidiary-to-produce-and-market-low-carbon-hydrogen
[37] https://www.world-nuclear-news.org/Articles/EDF-moves-into-the-hydrogen-market
[38] https://mcphy.com/en/press-releases/hydrogen-mobility-launch-of-the-augmented-mcfilling-hrs/
[39] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866374/Phase_1_-_EDF_-_Hydrogen_to_Heysham.pdf
[40] https://www.edfenergy.com/energy/nuclear-new-build-projects/sizewell-c/news-views/edf-joins-major-companies-unions-to-promote-moorside-clean-energy-hub

iv. Other Projects

In 2020, Hynamics signed a strategic partnership with software solutions company BaxEnergy, the two having collaborated since the previous year, to work on a hydrogen monitoring and control project in France. Hynamics installed BaxEnergy's software on a hydrogen refuelling station in the East of France, which is part of the Hydrogen Mobility Europe project[41].

Hynamics participates in the Interreg North-West Europe project H2SHIPS, intended to demonstrate the feasibility, both technical and economic, of hydrogen bunkering and propulsion for shipping and to identify the conditions required for successful market entry[42]. The total budget for the project is €6.33 million, of which €3.47 million the European Union. H2SHIPS is composed of two pilot projects: a new hydrogen powered port vessel, to be built in Amsterdam, and a hydrogen refuelling system suitable for open sea operation will be developed and tested in Belgium.

EDF partnered with Ørsted and several other companies with the intent to build a 30 MW electrolyser, to be powered by offshore wind at Heide on the west coast of Northern Germany, where a number of wind farms are sited[43]. The partnership group intend to also start work on initiating the design and construction of a 700 MW electrolyser, although significant research and engineering hurdles remain in place. The pilot project is budgeted at €89 million and received €30 million from the German Federal Ministry of Economic Affairs and Energy.

In November 2020, Framatome, the French nuclear reactor business that is owned by EDF, partnered, via its German arm, Covalion, with moBiel, a German transport company, to build a hydrogen refuelling station for a pilot project that intends to launch a hydrogen-powered bus fleet in Germany. Framatome will design and construct the hydrogen refuelling station, intended to be operational by the end of 2021[44].

[41] https://www.h2-view.com/story/baxenergy-and-hynamics-partner-on-hydrogen-monitoring-project/
[42] https://www.nweurope.eu/projects/project-search/h2ships-system-based-solutions-for-h2-fuelled-water-transport-in-north-west-europe/
[43] https://www.evwind.es/2020/08/04/orsted-secure-funding-for-renewable-hydrogen-project-westkuste-100-in-germany/76226
[44] https://www.powerengineeringint.com/hydrogen/framatome-and-german-bus-operator-team-up-on-hydrogen-fleet-pilot/

B. State Atomic Energy Corporation Rosatom (Rosatom)

i. Overview

Rosatom supports ambitious estimates for the growth of the commercial hydrogen market and claims to be focused on setting up large-scale production and the export of low-carbon hydrogen to the APAC region and EU member states, while also preparing to participate in local hydrogen production and use projects in both the Russian Federation and Europe.

Rosatom has been involved in hydrogen production and the development of associated technologies for a number of decades. Recently, the company has integrated the hydrogen economy into both its corporate research and wider development strategy[45]. Its development programme, 'Nuclear Science, Engineering, and Technology' includes proposals to advance its hydrogen-related activities.

ii. National Strategy

In the latest national Energy Strategy, adopted by the Russian Government and set to run until 2035, hydrogen was listed as the seventh most important component of the energy sector. Russia's first national hydrogen energy development roadmap was adopted by the Government of Russia and published in October 2020, outlining plans for 2020 to 2024. The roadmap was developed by a working group run by the Ministry of Energy which included representatives from Rosatom, Gazprom, and Sberbank as well as policymakers and Academics.

At present, Russia's hydrogen production is limited to domestic use but Pavel Sorokin, the Russian Deputy Minister of Energy, has stated a desire to see hydrogen exports of 200,000 tonnes a year by 2024 and 2 million tonnes by 2035[46]. Mr Sorokin cited a number of Asian countries, such as Japan, China and South Korea, as possible export targets, as well as European countries, including Germany and France. In terms of transmission, Russia is considering several scenarios which are currently under review, including transmission via gas pipelines as well as transporting it by ship in various possible chemical conditions. Though no Russian energy company has been included in the Hydrogen Council, which was established in 2017 in Davos and currently has 81 members, they are active participants of international hydrogen events such as the Hydrogen ministerial meeting in Tokyo and high-level bilateral meetings where hydrogen has been notably included as a topic for dialogue on future cooperation with partner countries.

iii. Technologies

Currently, "Hydrogen energy" is one of the key priority vectors of scientific and technological development and a promising strategic business growth priority at Rosatom. There is significant technological, scientific and research potential for the development of the principal hydrogen production methods – both steam methane reforming and electrolysis. In the next 2-3 years Rosatom plans to supply the market with its first designed technologies for hydrogen production, storage and transportation. At the same time, Rosatom claims to be positively motivated towards cooperation for the production of equipment with companies from other countries including localization of such production in the territory of the Russian Federation. Rosatom runs an extensive R&D programme on hydrogen technologies including those for hydrogen production, storage, transportation and utilization.

iv. Projects

Rosatom is focused on developing pilot projects on hydrogen energy development. In Autumn 2019, Rosatom signed a Memorandum of Understanding with the Region of Sakhalin and other Russian companies to develop a hydrogen-powered train service on the island of Sakhalin, taking on the role of the hydrogen supplier to the project[47]. The east of Russia, together with the APAC region, has been identified as a potential hydrogen export market. Thus in 2019 Rosatom signed an Agreement with Japan's Ministry of Energy, Trade and Industry (Agency for Resources and Energy) to jointly conduct a feasibility study on the potential of hydrogen exports from Russia to Japan[48].

The potential for low carbon hydrogen production is also assessed in the western part of Russia in the territories where nuclear power plants are located. It is assumed that excess power capacities could be utilized for hydrogen production via electrolysis for local supplies in Russia and, mainly, for export to Europe and Asia.

Last but not least Rosatom is looking into opportunities to participate in local industry and transport decarbonization projects in Europe and Russia, where the company could act as a developer, investor, owner and operator of green hydrogen production facilities for industrial users such as oil refineries and steel manufacturing facilities.

Rosatom claims to be open to establishing long-term strategic and technological partnerships for setting up efficient hydrogen production and building up supply chains.

[45] https://rosatomnewsletter.com/2020/07/25/era-of-hydrogen/#:~:text=As%20the%20global%20focus%20of,in%20the%20island%20of%20Sakhalin.
[46] https://asia.nikkei.com/Editor-s-Picks/Interview/Russia-plans-to-export-hydrogen-to-Asia-in-green-shift
[47] https://www.railwaypro.com/wp/russia-to-develop-its-first-hydrogen-train
[48] https://www.energymarketprice.com/energy-news/russia-and-japan-agree-to-collaborate-in-hydrogen-supply

Annex: Model Inputs (Section Three)

Electrolyser

	Unit	Value
Capacity	MW	10
Investment Cost	$ / kWe	1,400
Lifetime	Years	5
Efficiency	%	70
Power Requirement	kWh / kg H2	55

Electricity Generation

	Dedicated New Wind (Low)	Dedicated New Wind (High)	Existing Wind (Balancing)	Nuclear (Operating Excess)
Capacity Factor	33%	38%	10%	80%
Power Cost ($/MWh)	54	34	0	28.50
Levelised Cost of Hydrogen ($/kg)	12.46	9.81	27.12	5.63
Electrolyser Share of Levelised Cost	66%	73%	100%	60%

Other

	Unit	Value
Weighted Average Cost of Capital	%	4