Hydrogen Production with Operating Nuclear Power Plants

Business Case

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1. Background on hydrogen development and the role of nuclear energy

Key points:

- In the overall quest to create a decarbonized future, and with low carbon hydrogen gaining attention in hard-to-abate sectors, the present publication focuses on utilizing operating nuclear power plants for hydrogen production.
- An increasing number of countries are developing comprehensive hydrogen strategies, some of which include hydrogen production from both existing nuclear power capacity and hydrogen production from future nuclear power plants.
- Currently, the majority of hydrogen production is generated from fossil fuels which emit carbon dioxide (CO_2). Production of hydrogen using renewable energy or nuclear power does not emit CO_2, therefore these methods are expected to become the primary methods of low carbon hydrogen production in future.

Nuclear hydrogen as an energy carrier

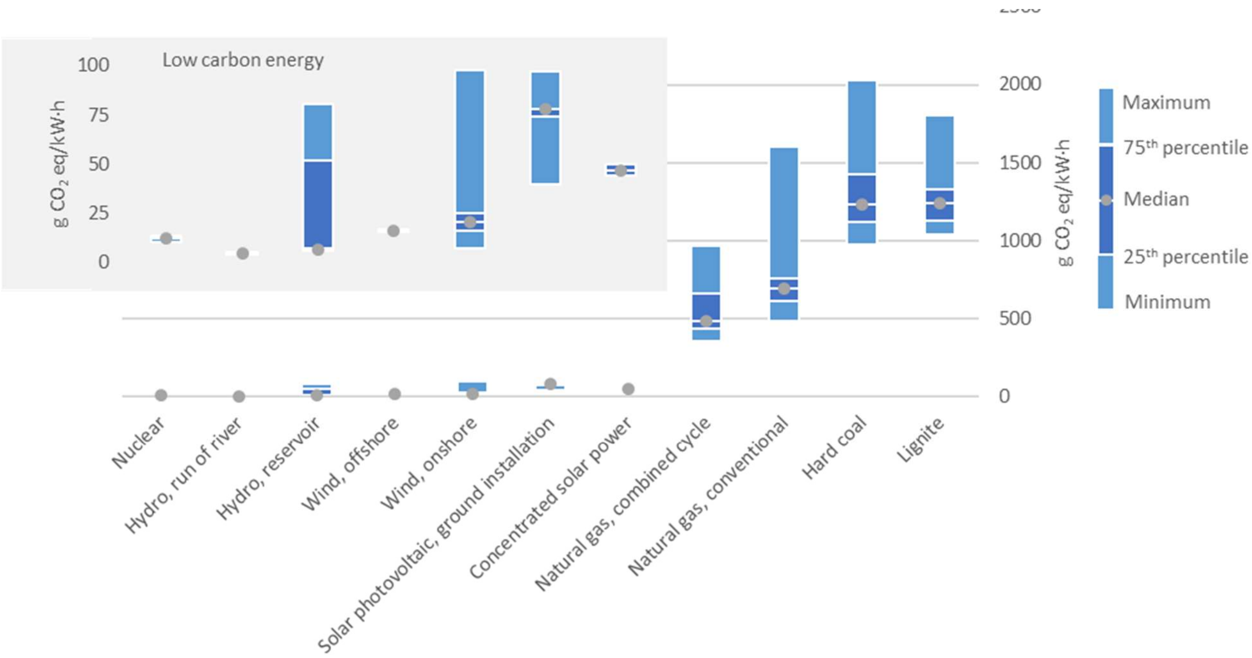
The role of nuclear hydrogen in decarbonization

The overall energy sector is responsible for nearly 75% of global greenhouse gas (GHG) emissions [World Resources Institute, 2020]. To reach climate targets by reducing global GHG emissions, it is therefore imperative to decarbonize the energy sector. To achieve decarbonization, carbon intensive sectors need to be electrified where this is technologically and economically feasible, and electricity generators need to transition from fossil fuels to low carbon generation sources, such as nuclear or renewable energy.

Figure 1 [IAEA, 2020] shows that although nuclear and renewable energy technologies are generally labelled as ‘low carbon’, all technologies nevertheless emit varying levels of CO_2 over their life cycles. Nuclear, hydropower and most wind technologies emit less than 25 grams of CO_2 equivalent emissions per kilowatt hour (gCO_2eq/kW·h) of energy produced, while solar power releases higher emissions (approximately 50-75 gCO_2eq/kW·h), primarily due to rare earth element compositions.

The potential of hydrogen as an energy carrier has attracted significant attention, due to the increased interest in mitigating global carbon emissions and the difficulty in electrifying certain sectors. If hydrogen is produced using low carbon energy sources (e.g. nuclear power), there are almost no CO_2 emissions, either from

Figure 1. Life cycle greenhouse gas emissions of electricity generation technologies (left), including a detailed view of the low carbon sources (right).



Note: g CO_2 eq/kW·h – grams CO_2 equivalent per kilowatt hour.
Source: adapted from Ref. IAEA [2020].

using the hydrogen as an energy carrier or from the production process. Whereas, if hydrogen is produced from fossil fuels there are significant CO_2 emissions released.

Efforts to widely deploy hydrogen in industry, transport and power sectors will support decarbonization. Hydrogen is a versatile energy carrier that can help decarbonize certain hard-to-abate sectors that are unable to undergo direct electrification because of technological or economic difficulties.

The International Energy Agency (IEA) has identified hydrogen and hydrogen-based fuels as one of the seven key pillars of decarbonization [IEA, 2023]. According to the Energy Transitions Commission (ETC), which is an international thinktank focused on achieving net zero by mid-century, hydrogen can play a major role in decarbonization, whether it is used directly or in the form of derived fuels in sectors where direct electrification is unfeasible or uneconomical [ETC, 2021]. Nuclear Europe (formerly FORATOM) considers it essential to adopt all commercially mature low carbon energy sources, including nuclear power, which can produce hydrogen [nucleareurope, 2021].

Nuclear power can provide both electricity and heat 24/7 to support the efficient production of hydrogen through diverse processes. Today, existing nuclear power plants (NPPs) are operating in energy systems with increasing shares of variable renewable energy. Hydrogen provides the option of storing energy when there is a surplus energy supply from renewables and increases the flexibility of these hybrid systems. In addition, the sale of hydrogen produced could be a valuable alternative revenue stream for NPPs with surplus power.

The present International Atomic Energy Agency (IAEA) publication examines the option of using operating NPPs for hydrogen production and includes a discussion on how and when the technology is economically feasible.

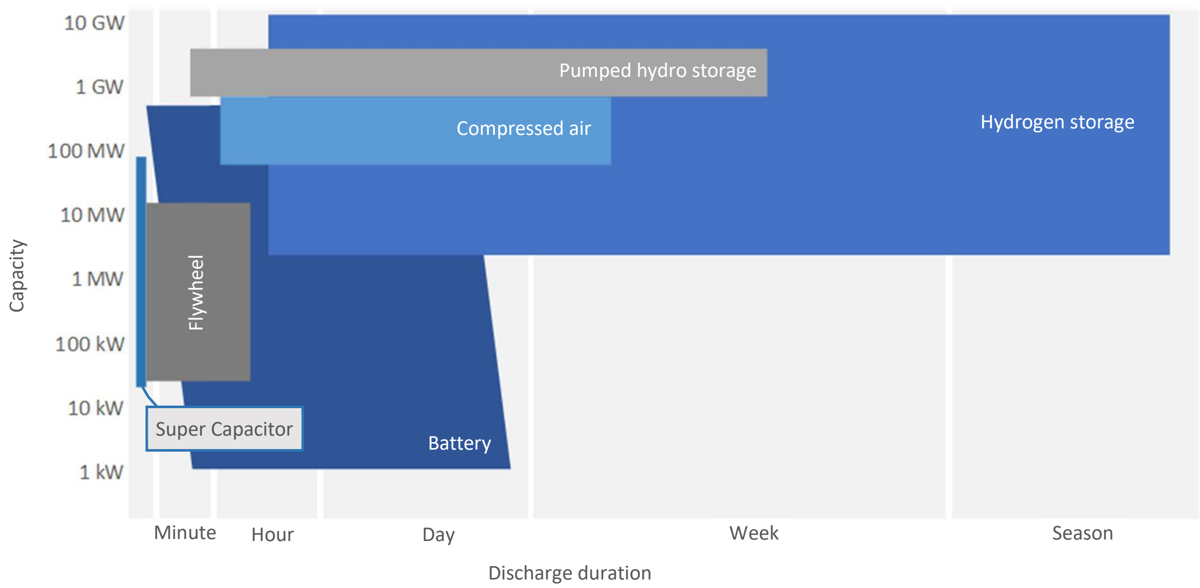
Potential uses of hydrogen

The potential uses of hydrogen as an energy carrier vary widely across many sectors of the global economy. Regional and national requirements will dictate the best use of hydrogen in each country, but hydrogen production, aimed at a range of applications across sectors, will contribute towards decarbonization.

Industry: Low carbon hydrogen can contribute significantly to the decarbonization of some industrial processes. Many industries use fossil fuels as chemical feedstock for processing. For example, some fossil fuels are used to produce hydrogen which is then used as feedstock to produce chemicals such as ammonia. In other processes, such as steel production, coal and coke are currently used to remove oxygen, but if hydrogen were used to reduce iron ore there would be no CO_2 emissions related to the process.

Transport: Electric vehicles are among the most attractive technologies for decarbonization of the transport sector, but this is not the only way to decarbonize this sector. Hydrogen has a higher energy density than commercialized battery storage technologies and thus is well suited for transport over long distances due to the reduced weight compared to battery storage. If hydrogen were to be commonly used as a fuel in the transport sector, this could reduce the emissions of large, long-distance transport, such as shipping and aviation.

Figure 2. Energy storage technologies



Note: MW – megawatt; GW – gigawatt.
Source: adapted from Ref. IAEA [2020].

Electric power: Hydrogen can be used as an energy storage technology to help mitigate the fluctuations in renewable output caused by the integration of large shares of variable renewables into the energy mix. Figure 2 [IEA, 2015] on the previous page shows the characteristics of several energy storage technologies with respect to capacity and discharge duration. The battery, currently the most widely deployed means of storage, has a comparative advantage in meeting 'short term' (sub-hourly) system imbalances due to readiness. Hydrogen storage, on the other hand, is effective for large scale and long-term power storage because of its low energy loss over time and the scalability of hydrogen tanks. In future, it will be important to create an appropriate system that combines energy storage technologies based on such characteristics, with the role of hydrogen as an energy storage technology expected to expand.

Hydrogen outlook

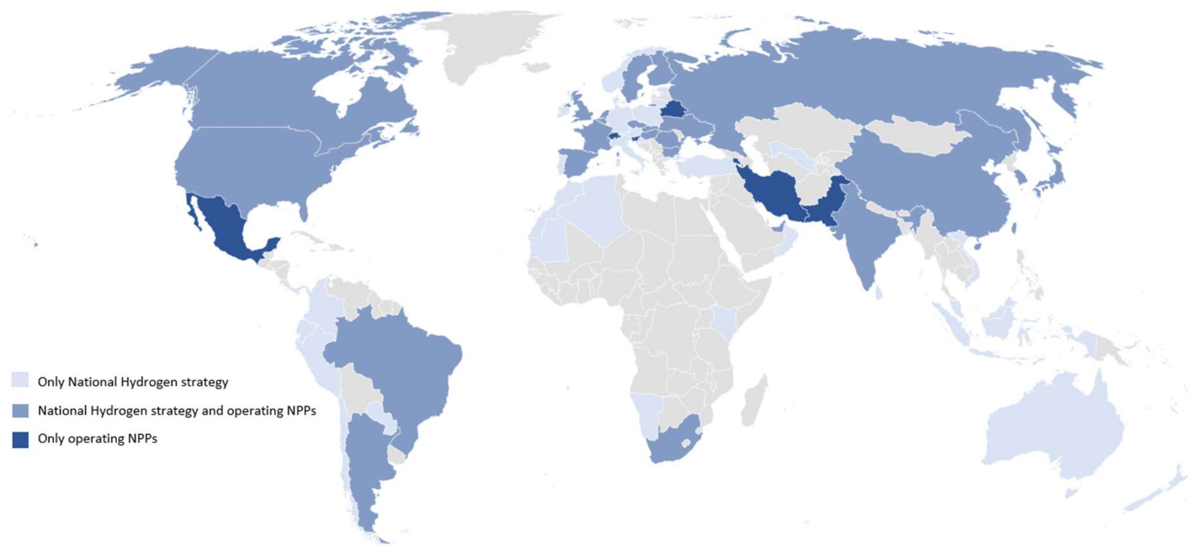
Given that hydrogen is expected to play an important role in emission reductions by 2050, the demand for hydrogen will therefore increase significantly over this time frame. The IEA estimates that global hydrogen demand will grow from 90 million tonnes in 2020 to 430 million tonnes in 2050 [IEA, 2023]. While at present most hydrogen is produced from fossil fuels, in future much of this hydrogen will need to come from low carbon sources to meet decarbonization goals. The IEA estimates that by 2050 more than 60% of global hydrogen production will come from water electrolysis [IEA, 2023].

Recent hydrogen policy developments

National interest in hydrogen has grown rapidly in recent years. Figure 3 [HyResource, 2024] shows that over 60 countries have developed comprehensive hydrogen strategies, reflecting their county's energy needs, environmental goals and economic objectives beyond research and development (R&D) programmes and vision documents. From the 32 states with operating NPPs, over 65% have hydrogen strategies, with many of the strategies describing using existing nuclear or future nuclear developments, such as small modular reactors, and high temperature gas cooled reactors (HTGRs), for hydrogen production. The Nuclear Hydrogen Initiative, which was established by various hydrogen and nuclear organizations, has also made several recommendations for policy actions, one of which is that hydrogen policies and roadmaps should include: (a) mention of the importance of nuclear hydrogen production in decarbonization; (b) explicit goals and metrics for nuclear hydrogen production; and (c) a hydrogen hub with nuclear hydrogen production facilities [Nuclear Hydrogen Initiative, 2022].

Electricity and heat from NPPs can be harnessed to produce hydrogen, and yet most global energy scenario projections currently limit nuclear energy's role to the power sector. Despite many countries adopting or announcing their intentions to create national hydrogen development strategies, only a few countries have active projects related to nuclear hydrogen production, and even these are in the nascent stages.

Figure 3. National hydrogen strategies and countries with operational NPPs as of August 2024



Source: based on data from Ref. HyResource [2024] and Ref. (2024)

These national hydrogen development strategies may offer a promising future for nuclear hydrogen production. The following paragraphs provide specific descriptions of some national hydrogen strategies with respect to hydrogen production using nuclear power.

Canada [Ministry of Natural Resources, Canada, 2020] considers nuclear power to be an abundant, low carbon resource for hydrogen production, and Canada's development strategy includes hydrogen produced via electrolysis using off-peak electricity from existing NPPs. For example, an economic feasibility of nuclear hydrogen production in Ontario at the Bruce Nuclear Generating Station has been conducted and a feasibility study for a hydrogen hub is underway in Toronto. However, the country has noted some important infrastructure challenges. The planning document, for example, lists obstacles related to hydrogen deployment at scale, which include the storage of high volumes of hydrogen at existing nuclear sites.

Czech Republic [Ministry of Industry and Trade, Czech Republic, 2021] has a limited number of hours of viable sunshine and wind conditions, necessitating the use of other low carbon technologies for power production. The country is therefore considering use of nuclear power for hydrogen production to meet its decarbonization goals. The Czech Republic has deemed it much more efficient to equip existing NPPs with large electrolysers and hydrogen storage on-site to limit energy losses, rather than placing them close to end users. However, the strategy also mentions that the additional costs and energy losses associated with transporting hydrogen from the source of production to the location of consumption need to be considered.

Hungary [Ministry of Innovation and Technology, Hungary, 2021] is interested in low carbon hydrogen in the short and medium term to rapidly reduce emissions and establish a viable hydrogen market. The strategy mentions that the country will not ignore opportunities to produce low carbon hydrogen using electricity from nuclear power. To decarbonize the industrial sector, Hungary plans to establish two new hydrogen valleys, the Transdanubia hydrogen ecosystem and Northeast hydrogen valley, by 2030. For the Transdanubia valley, plans are in place to produce hydrogen using electricity from the existing Paks NPP, and additional 'green electricity', to supply hydrogen for the ammonia and refinery industries. Further hydrogen demand is also expected due to the potential use of hydrogen for an iron mill and cement production facility in the region.

Poland [Ministry of Climate and Environment, Poland, 2021] has indicated that once its first NPP begins operation (scheduled for 2033), electrolysis using electricity from NPPs will be one of the technologies used to produce low carbon hydrogen. To ensure that hydrogen can be produced from electricity generated at NPPs, Poland considers planning the construction of the hydrogen production facilities in advance of building the associated NPP. To ensure hydrogen production from NPPs is cost competitive, the strategy suggests large scale hydrogen production using surplus electricity produced during the night could reduce costs. The country considers that in the future it will be possible to produce hydrogen using heat from a HTGR and started cooperating with Japan on this technology in 2020.

Slovakia [Ministry of Economy, Slovakia, 2021] considers that sustainable hydrogen production is necessary to introduce and expand the domestic and international hydrogen market in an efficient manner. For this reason, the country is considering hydrogen production using surplus electricity from NPPs as one method of producing hydrogen.

Republic of Korea (Roadmap for revitalizing the hydrogen economy, 2019) The government of Republic of Korea announced the Hydrogen Economy Roadmap to promote the development and use of hydrogen energy in January 2019. On 4 February 2020, the South Korean government promulgated the Hydrogen Economy Promotion and Hydrogen Safety Management Act ("Hydrogen Act"), which came into force on 5 February 2021. The Hydrogen Act is now the central legislation regulating the hydrogen industry, while the Act on the Promotion of the Development, Use and Diffusion of New and Renewable Energy (the "Renewable Energy Act"), which was last amended in March 2017, will be used where an issue is not covered.

The United Kingdom [Department of Business, Energy and Industrial Strategy, UK, 2021] has committed to a 'twin track' approach to hydrogen production, supporting both electrolytic hydrogen from low carbon sources, and employing carbon capture, utilization and storage (CCUS), when fossil fuels are required for hydrogen production. This approach aims to ensure that the country supports a wide variety of production methods in an effort to deliver the volume of hydrogen necessary to meet the country's net zero target by 2050. Hydrogen production using existing and advanced nuclear power is one of several technologies currently in the demonstration phase in the UK. The country expects to learn by producing hydrogen through readily available low temperature electrolysis with existing NPPs during the 2020s. The range of production technologies will then be expanded to include high temperature electrolysis and thermochemical water splitting from the 2030s onwards, to enable large-scale commercial production.

United States of America (USA) (DOE, U.S. National Clean Hydrogen Strategy and Roadmap, 2023) released a comprehensive hydrogen roadmap which focused on three key strategies. As part of the roadmap, large scale hydrogen production from renewables, nuclear, and fossil fuels with carbon capture storage, are all considered as clean hydrogen. The first strategy is to target clean hydrogen to address hard-to-abate sectors, such as industrial applications, transportation, and power sector applications. The second strategy is to reduce the cost of producing clean hydrogen and to reduce both the storage and delivery costs. The target cost of producing clean hydrogen in the USA is $2/kg by 2026 and $1/kg by 2031. As part of the Inflation Reduction Act (IRA), the clean hydrogen tax credit (45 V) was proposed in December 2023, this credit will provide up to $3/kg for clean hydrogen production, depending on the level of carbon intensity of the production method (DOE, 2023a). The proposed regulations included a set of restrictions named the 'Three Pillars' which are: incrementality, temporal matching and deliverability. In the current proposed form of the tax credit, the pillar of incrementality would require electricity to be produced at the plant no more than 36 months before the plant starts producing hydrogen – this means that only one nuclear plant in the USA would be eligible. The Government is under significant pressure from nuclear hydrogen projects to include hydrogen production from existing nuclear in the tax credits and for the economic feasibility of such projects. The third strategy of the hydrogen roadmap is to focus on regional clean hydrogen hubs, with the recognition that hubs can provide large-scale hydrogen close to their end users and can provide economic benefits to local communities. Seven hydrogen hubs were selected around the country, three of which include clean hydrogen production from NPPs. This streamlined approach has reduced the amount of nuclear hydrogen projects in the country, with financial support targeted at the projects with the most promise for cost competitive clean hydrogen. For example, the Davis-Besse hub, and Palo Verde projects have both been scrapped due to difficult economic conditions and lack of financial support from government.

European Union's (EU) (European Commission, 2020) hydrogen strategy has five key areas of action: support production and demand; create a hydrogen market and infrastructure; research and cooperation; and international cooperation. In 2021 the Fit-for-55 package was presented, this translated the EU strategy on hydrogen into a policy framework. In 2024, the European Parliament agreed to include low-carbon hydrogen and gas production within their 2030 and 2050 climate targets (European Commission, 2024). Nuclear energy is not supported by all EU member states, however by including a clause on low carbon hydrogen, hydrogen production by NPPs is officially recognised by the EU as contributing the supply of clean hydrogen. The EU Commission also set up the European Hydrogen Bank to support the production of hydrogen from renewables in Europe.

People's Republic of China (National Energy Administration, 2022) published their hydrogen strategy, with a medium to long term plan focusing on the production of green hydrogen up to 2035. China is currently the world's largest producer and consumer of hydrogen. China's substantial market size and industrial infrastructure offer significant potential to achieve economies of scale in hydrogen production and deployment. A key distinction in China's hydrogen strategy is that it is not limited to a singular national plan; instead, it encompasses a wide range of regional strategies, each tailored to local demand and resources. The combined targets of all the regional strategies are ambitious, they are five to twelve times the national target for renewable hydrogen by 2025. Although China has added over 34 GW in nuclear power to the grid in the last 10 years, the national hydrogen strategy is focused on a large expansion of hydrogen production, primarily, from renewable energy sources. A key challenge in China is to transport the hydrogen to centres of hydrogen demand, with the potential for a large increase in hydrogen produced from renewables in the northwest of the country and a potential growth of hydrogen demand in the east and southeast of China.

India (Ministry of New and Renewable Energy, 2023) announced their hydrogen strategy in 2023, with a focus to transform the country into a global hub for: hydrogen production, hydrogen usage and export of green hydrogen. Although India has over 8 GW of existing nuclear energy and seven more reactors in the construction phase, the national hydrogen strategy does not discuss hydrogen production from nuclear energy. Instead, the strategy focuses solely on hydrogen production from renewable energy.

United Arab Emirates (UAE) (Ministry of Energy & Infrastructure, 2023) aims to make the country one of the largest producers of low-emission hydrogen by 2031. The UAE has a technology neutral approach to low carbon hydrogen and therefore the strategy supports hydrogen production from fossil fuels with carbon capture, renewables, and nuclear energy. Since the commissioning of the Barakah NPP, the UAE has over 5GW of nuclear power capacity which could be used for hydrogen production.

Primary hydrogen production methods

Unlike natural gas, hydrogen needs to be produced from other matter by a chemical process using a supply of energy in the form of heat and/or electricity. The most common methods of producing hydrogen are 1) thermochemical production from fossil fuels, most commonly steam methane reforming (SMR), 2) electrolytic processes, where water is split into hydrogen and oxygen using a source of electricity, and 3) thermochemical water splitting.

1) Production from fossil fuels

Currently, hydrogen is primarily produced from fossil fuels, which emit carbon dioxide (CO_2) during hydrogen production. For this reason, carbon capture and storage (CCS) is being explored as a solution before the CO_2 enters the atmosphere.

The carbon intensity of the hydrogen production process can also vary, particularly if nuclear power is involved in the production process. If heat from nuclear power, in lieu of fossil fuels, provides high temperatures to perform hydrogen production processes, emissions will decrease.

Steam methane reforming

The steam methane reforming reaction converts methane into hydrogen (H_2) and carbon monoxide (CO) using heat and steam. Since the reforming reaction is an endothermic reaction, a temperature of about 800°C is required. Normally, a part of the raw material is burned in a burner to obtain the necessary heat. H_2 and CO_2 are obtained through the water-gas shift reaction, in which water further reacts with the resulting CO.

(1) $CH_4 + H_2O \rightarrow CO + 3H_2$

(2) $CO + H_2O \rightarrow CO_2 + H_2$

Coal gasification

To produce hydrogen from coal, oxygen (O_2) is first added to coal to produce CO_2 from the coal through combustion. The CO_2 again reacts with the coal to produce CO. Further reaction of the CO with water vapour generates H_2 and CO_2.

(1) $C + O_2 \rightarrow CO_2$

(2) $C + CO_2 \rightarrow 2CO$

(3) $CO + H_2O \rightarrow CO_2 + H_2$

Technologies reducing carbon emissions

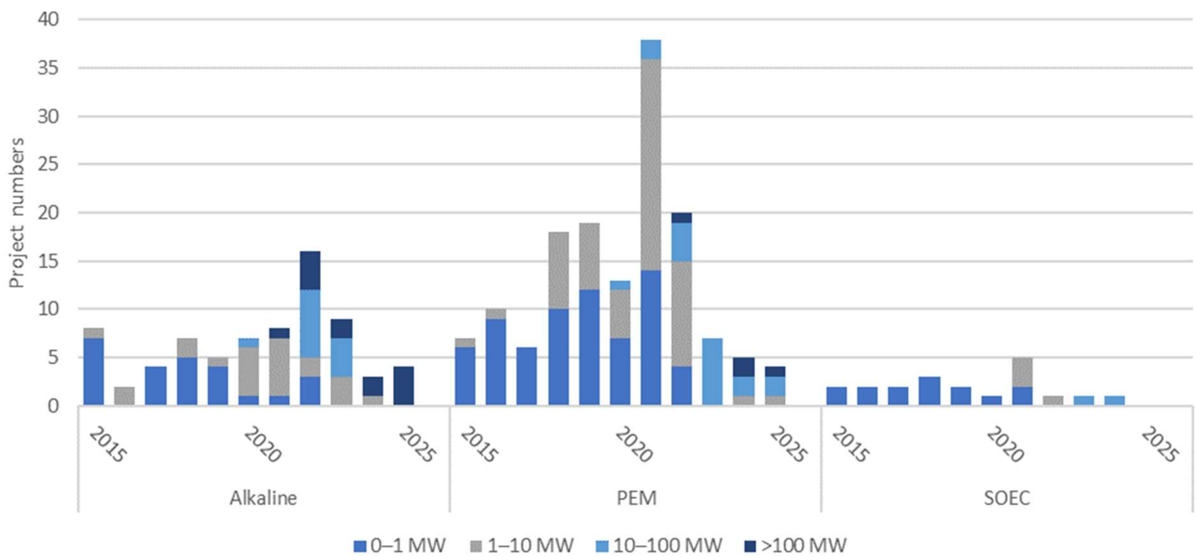
Steam methane reforming and coal gasification processes emit large amounts of CO_2, but these

Table 1. Technoeconomic characteristics of electrolyser technologies

	LTE		HTE
	Alkaline	PEM	SOEC
Operating temperature	60–80°C	50–80°C	650–1000°C
Electrical efficiency (LHV)	63–70%	56–60%	74–81%
CAPEX	US $500–1400/kWe	US $1100–1800/kWe	US $2800–5600/kWe
Stack lifetime (operating hours)	60 000–90 000 hours	30 000–90 000 hours	10 000–30 000 hours
Load range (relative to nominal load)	10–110%	0–60%	20–100%
Operating pressure	100–3000 kPa	3000–8000 kPa	100 kPa

Note: SOEC – solid oxide electrolyser cell; LHV – lower heating value; CAPEX – capital expenditure; kWe – kilowatt electric.
Source: adapted from Ref. IEA [2019].

Figure 4. Electrolysis project numbers



Note: Years refer to the planned start of operations, and only projects with a known start year are considered.
Source: based on data from Ref. IEA [2021b].

emissions can be reduced through CCUS, where the stored CO_2 is then used for another purpose, or through CCS where CO_2 is captured and stored before it enters the atmosphere.

2) Electrolytic processes

Today's main electrolyser technologies can be divided into two types: (a) low temperature electrolysers (LTEs); and (b) high temperature electrolysers (HTEs). For low carbon hydrogen production, these technologies need to use electricity from renewable energy, nuclear power, or from fossil with CCS & CCUS (even if in this later case it makes more sense to use steam methane reforming). Table 1 [IEA, 2019] shows that each electrolyser has its own characteristics and is used according to the scale and purpose of the project.

Low temperature electrolysis

Low temperature electrolysis is an established technology that has already been deployed on a commercial scale. At present, it is an essential technology for producing large amounts of hydrogen using nuclear power and renewable energy.

LTEs mainly consist of alkaline electrolysers and proton exchange membrane (PEM) electrolysers. While low carbon hydrogen is getting more attention, the demand for both technologies is increasing, which is ultimately helping each of these technologies to reach commercial scale. Figure 4 [IEA, 2021b], on the previous page, shows that alkaline electrolyser projects currently have a higher number of projects — exceeding 100 MW — compared to PEM electrolyser projects. On the other hand, there has been a higher total number of PEM electrolyser projects compared to alkaline electrolyser projects. This trend makes sense given the attributes of each technology.

Alkaline electrolysers are a mature technology used on a commercial scale, with project sizes reaching over 100 MW. The largest of these alkaline electrolyser projects are in China, with Baofeng Energy installing 150 MW of alkaline and Sinopec installing 260 MW alkaline electrolysers, both for green hydrogen production. Table 1 shows that alkaline electrolysers have relatively low capital costs, mainly due to the absence of precious materials, such platinum, compared to PEM electrolysers.

PEM electrolysers perform electrolysis of water using solid polymer electrolytes that help to convert energy to hydrogen. PEM electrolysers are relatively small, making them potentially more attractive than alkaline electrolysers for dense urban areas. PEM as LTEs electrolysers can handle a changing load but with faster ramping rate, which is particularly useful for producing hydrogen from renewable energy. PEM electrolysers can also produce compressed hydrogen for decentralized production and storage at refuelling stations, and there is the capability to provide frequency containment reserves which can help the grid respond to frequency changes within seconds. However, PEM electrolysers require expensive electrode catalysts (e.g. platinum, iridium) and membrane materials, and their lifetime is currently shorter than that of alkaline electrolysers. Their overall costs are also currently higher than those of alkaline electrolysers.

In addition to these low temperature electrolysis technologies, there is also the anion exchange membrane (AEM) electrolyser, which is in R&D, with some companies developing small pilot projects. The AEM is a device that changes the proton conductive electrolyte membrane of the PEM electrolyser to an anion conductive material to enable water electrolysis under alkaline conditions. The advantage of the AEM electrolyser is that it does not require precious metals for catalysts, thus reducing costs. However, current electrolytic membranes are short-lived and there is active R&D to develop more durable materials for the membranes to ensure long term stability during operation.

High temperature electrolysis

High temperature electrolysis uses heat in addition to electricity to produce hydrogen. As the temperature increases, a larger proportion of energy for electrolysis is supplied by heat, and the amount of energy from electricity decreases, thus enabling electrolysis with less electricity. The overall efficiency of the process is therefore higher than for low temperature electrolysis. The Nuclear Industry Association (NIA) [Nuclear Industry Association, 2021] has reported, that electrolysis taking place between around 600–1000ºC requires approximately 30% less energy than electrolysis using LTEs. The NIA also underlined that even with the use of low temperature steam (150–200ºC) from existing NPPs, efficiency could be improved. Although the heat supplied by current NPPs may not be sufficient for direct HTE, heat exchangers could be used to achieve the operating temperatures required. This method would make it possible to use heat from existing NPPs to increase the efficiency of electrolysis.

The solid oxide electrolyser cell (SOEC) is a key technology for the HTE. SOEC's use ceramics as the electrolyte and have low material costs. On the other hand, one key challenge for those developing SOEC electrolysers is addressing the rapid degradation of materials that results from the high operating temperatures. To increase SOEC system size, slower degradation processes or materials will need to be developed and the appropriate replacement timing of degraded cells will need to be studied to optimize costs. The technology is still in the R&D phase, and compared to LTE projects, both the number and size of projects are small. In addition, SOEC projects that use heat from NPPs need to be installed in proximity to the NPP sites, therefore the utility must meet all the different engineering codes and standards, as well as related regulations. HTE nevertheless remains an attractive technology for nuclear power, since it can produce hydrogen using both electricity and heat efficiently.

3) Thermochemical water splitting

Water starts splitting into hydrogen and oxygen at temperatures above 2200°C and is required to reach 3000°C to split half of the molecules. However, it is difficult to secure such high temperatures, and materials that can withstand such temperatures are limited. One method under consideration is to indirectly split water into hydrogen and oxygen by combining various reactions. Among the different cycles, the sulphur-iodine (S-I) and copper-chlorine (Cu-Cl) cycles are promising [Suppiah, 2020].

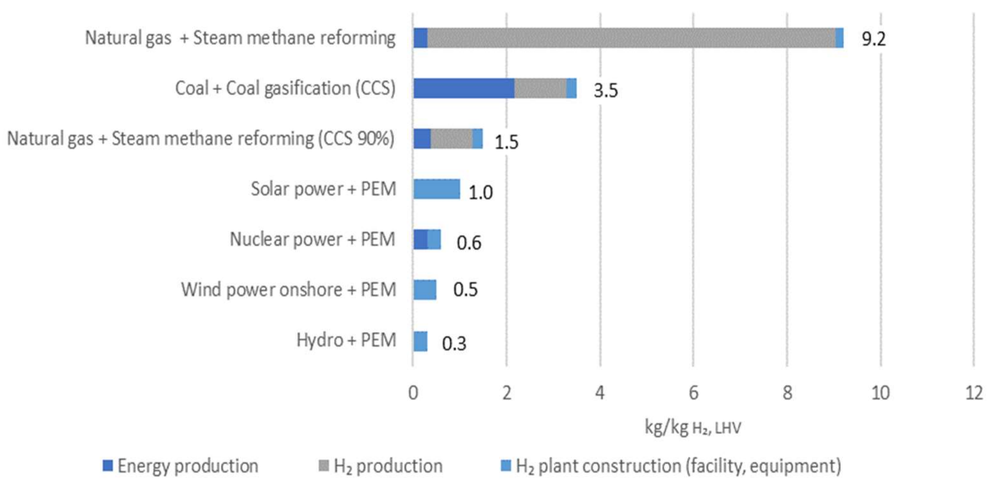
In the S-I cycle, it is possible to decompose water into hydrogen and oxygen with heat at about 900ºC. The HTGR design is also suitable for this technology, as it can provide heat of 850–950ºC. Hydrogen production via the S-I process was successfully operated for 150 hours in 2019 using test equipment made of practical and industrial material [JAEA, 2021a]. During demonstration, in addition to the challenge of heat resistance, challenges in relation to equipment blockage due to iodine precipitation, and corrosion caused by hydrogen iodide and sulfuric acid were overcome. The next challenge for practical application is to develop a system that can produce large amounts of hydrogen for much longer periods in a stable manner.

In comparison with other thermochemical cycles, the Cu-Cl cycle requires relatively low temperatures of up to 530ºC, and so it may be well suited for coupling with small modular reactors. For the same reason, construction materials and corrosion issues are more manageable than for other thermochemical cycles. However, some unique challenges involve solid handling requirements and developing corrosive resistant materials in the high temperature molten copper chloride environment. This method, using the Cu-Cl cycle, is still approaching laboratory scale demonstration.

Emissions from hydrogen production

Figure 5 [Hydrogen Council, 2021a] shows the various methods used to produce hydrogen, each with their own lifetime CO_2 emissions. There is a significant reduction in CO_2 emissions with the use of CCS or by using PEM, compared to SMR and coal gasification. CO_2 capture rates using CCS are expected to be very high, at about 80-90%. However, this statistic does not imply that CO_2 emissions can be reduced by 80-90%, because energy is required to peform the extraction, capture, transport and sequestration processes. In addition, fugitive methane emissions prior to combustion is the biggest issue, as over a period of 100 years a tonne of methane is 28 times more powerful than one tonne of carbon dioxide. Even with CCS, the resulting emissions are still large compared to the emissions from electrolysis. In the case of hydrogen production using electrolysis, there are no direct emissions, although there is a large difference in terms of indirect emissions depending on the individual method used. Emissions from solar are particularly large compared with other low carbon methods, due to the considerable emissions produced during the manufacturing, delivering and maintenance of solar panels.

Figure 5. Carbon equivalent emissions by hydrogen production pathways in 2030



Note: Energy production = indirect emissions from producing the supply of main input into the H_2 plant (natural gas, coal, electricity): H_2 production = direct emissions from producing H_2. Values for natural gas increase to 11.0 and 3.9 (with CCS) if the natural gas is transported 5000 km prior to use, compared to 1700 km in the case of Figure 5.

Source: adapted from Ref. Hydrogen Council [2021a].

2. The business case for nuclear hydrogen

Key points:

- Electrolysis is more expensive for hydrogen production than fossil fuel-based processes, due to the cost and large quantity of electricity required.
- To improve the profitability of hydrogen production, there are several ways to decrease the cost of the electricity for example by using electricity from NPPs in long term operation (LTO), or by combining renewable energy and nuclear power. To improve the economic feasibility further it is important to improve the efficiency of the electrolyser to produce more hydrogen for the same amount of electricity supplied. Finally, a trade-off shall be found between load factor of the electrolyser and chasing low electricity prices.
- Although current hydrogen demand is limited to some sectors, such as oil refining and the chemical industry, it is expected that other sectors, such as long-distance transport, steel production and power storage, will produce increased hydrogen demand. Cluster projects involving nuclear power have therefore been started as a strategy to stimulate demand.

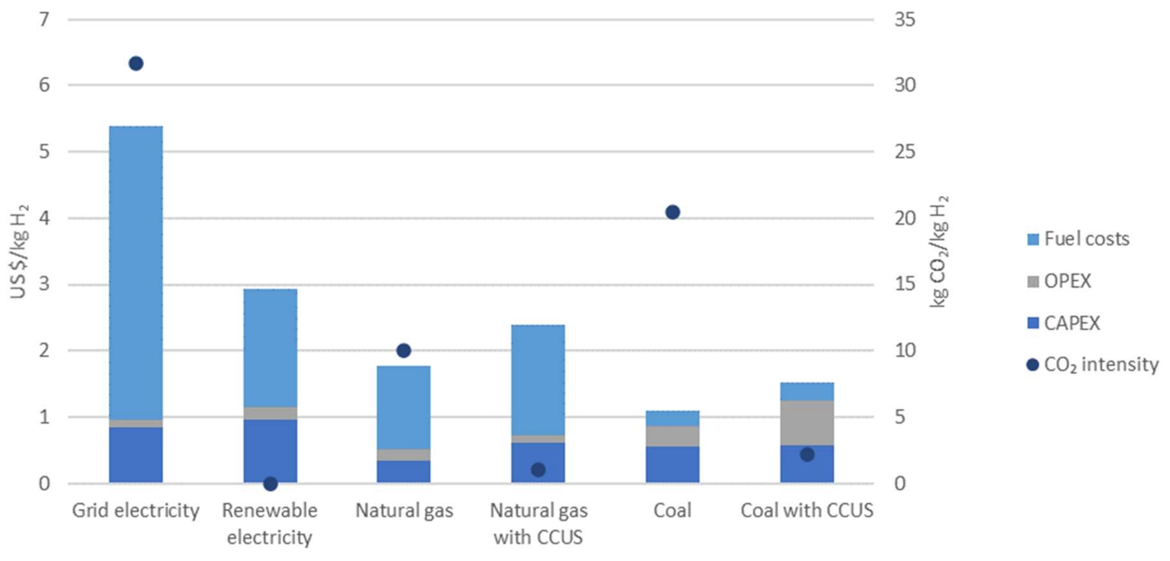
Cost breakdown and revenue maximization

Cost breakdown

Most hydrogen produced in the world today is still derived from fossil fuels, through SMR or coal gasification. In 2023, nearly 75% of hydrogen production was from unabated natural gas, 20% production was from unabated coal, leaving only 5% produced by low carbon methods (IEA, 2024). For hydrogen to fulfil its potential as an energy carrier in a decarbonized economy, it would need to be produced in large quantities and in a sustainable way. However, for this to happen, low carbon hydrogen production needs to be economically feasible compared to alternative production methods.

When discussing the economics of hydrogen, the focus is generally on the cost of production per kilogram. Figure 6 [IEA, 2019] shows that in China, for example, the cost of hydrogen production using natural gas without CCUS was assumed to be about $1.80/kg as of 2018, while this cost would increase to $2.20/kg by adding CCUS. The cost of hydrogen production using coal gasification is even lower, at $1.00/kg without CCUS and $1.50/kg with CCUS. Hydrogen production using electrolysis is more expensive than other methods, at $2.90/kg using electricity generated by renewable sources and $5.50/kg using electricity from the grid. In this case, the difference in hydrogen production cost of natural gas with CCUS, and electrolysis with renewable electricity, is relatively small, this is likely due to China importing natural gas at relatively high costs and having enough renewable electricity at relatively low costs (assumed to be $30/MW·h in this case). As shown in the breakdown of hydrogen production costs, in Figure 6, electricity or fuel costs account for a large proportion of the cost of hydrogen production. When hydrogen is produced by electrolysis, the cost of electricity accounts for a large proportion of the cost, at about 60–80%.

Figure 6. Hydrogen production costs in China in 2018



Note: OPEX – operational expenditure.
Assuming a renewable electricity cost of $30/MW·h power price, electricity prices in China = $113/MW·h.
Source: adapted from Ref. IEA [2019].

As most of worldwide hydrogen production is currently SMR from gas and coal, the hydrogen production price is dependent on the cost of natural gas and coal. For example, in 2022 when prices of natural gas increased, due to sanctions policy placed on Russia, the price of hydrogen production in Europe increased from $2.8/kg to $6.0/kg (Europe, 2023). Prior to the start of the war in Ukraine, the historical world average of cost of hydrogen production was $1.0-3.0/kg. For low carbon hydrogen to compete with hydrogen produced from fossil fuels, the cost needs to be reduced to be cost competitive.

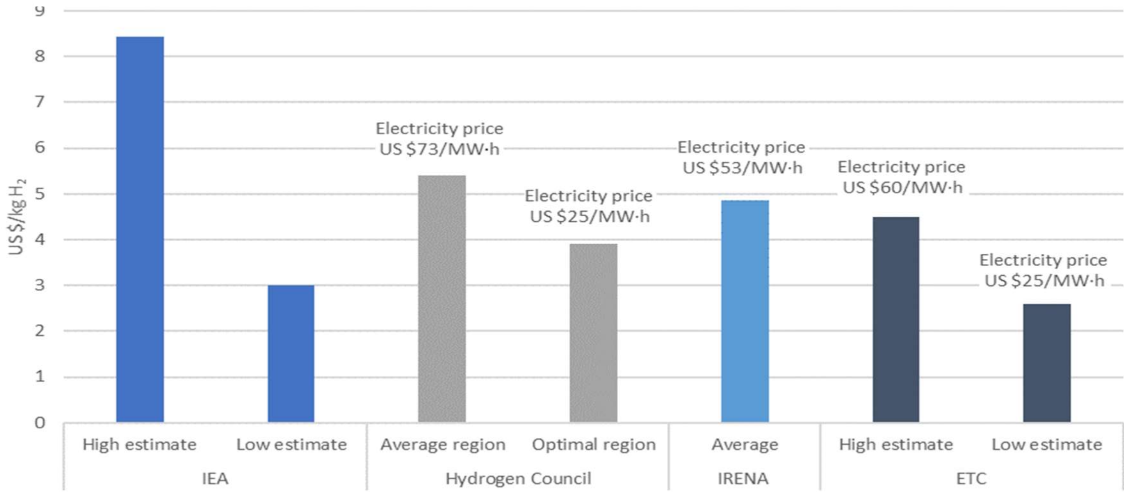
Figure 7 illustrates how the cost of hydrogen production from renewable energy differs across the world depending on the renewable generation capacity in each region. The IEA has assumed a high case of 8.50/kg H_2, and the ETC has assumed a low case of $2.80/kg H_2 [IEA, 2021c; Hydrogen Council, 2021b; IRENA, 2020; ETC, 2021].

Globally, the costs of hydrogen production from coal or natural gas by SMR are the cheapest methods of producing hydrogen, with the costs of producing hydrogen from renewables and nuclear energy up to 5-8 times higher than from fossil fuels (IEA, 2023).

Revenue optimization

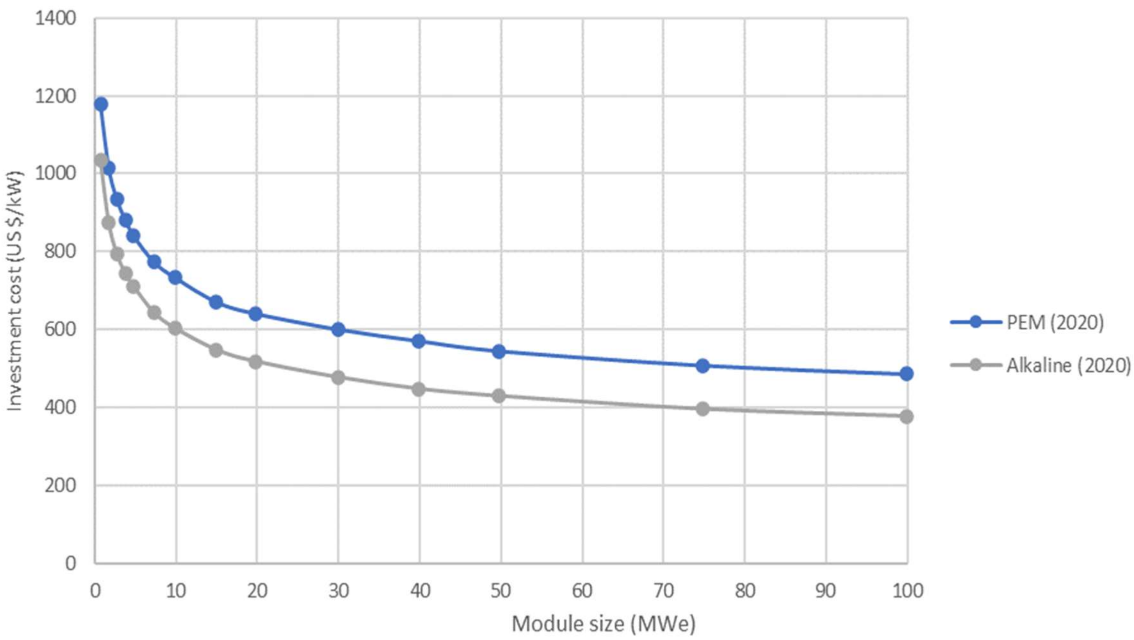
Three main parameters are crucial for the profitability of hydrogen production: (a) the capital investment for the electrolyser; (b) the cost of electricity used in the

Figure 7. Hydrogen production costs with renewable energy in 2020



Source: based on data from Ref. IEA [2021c]; Hydrogen Council [2021b]; IRENA [2020]; Energy Transition Commission

Figure 8. Electrolyser investment cost as a function of module size for various technologies



Source: adapted from Ref. IRENA [2020].

production process; and (c) the capacity factor of the electrolyser.

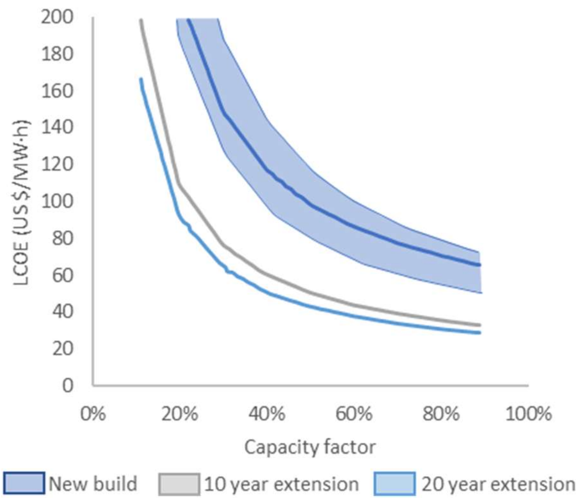
(a) Capital costs

The most expensive component of low temperature electrolysis is not the electrolyser itself but rather all the supporting components and auxiliary systems needed to deliver energy. Figure 8 [IRENA, 2020], on the previous page, shows that increasing the module size can lead to benefits in economies of scale because investment costs decrease with module size. A 100 MW alkaline electrolyser can deliver 10 times the power of a 10 MW electrolyser at approximately 30–40% of the cost per unit, as shown in Figure 8. However, this saving is highly dependent on stack design and will vary between manufacturers. As a large power generation facility, NPPs are well suited for the installation of a large electrolyser, from around 100 MW to 1 GW in size.

(b) Electricity costs

The cost of the low emission electricity used by the electrolyser can be further reduced by using nuclear power and renewable energy, which have lower marginal costs compared to traditional fossil fuel generators. Figure 9 [IEA, OECD NEA, 2020] shows that the levelized cost of electricity (LCOE) for new build NPPs is assumed to be around \$70/MW·h at an 85% capacity factor, while the LCOE for existing NPPs in LTO is assumed to be around \$30/MW·h at an 85% capacity factor, depending on the extension period. The LTO of existing NPPs is defined as the operation of NPPs beyond the typical design life of 40 years. The overnight cost of constructing NPPs varies globally, with Europe facing some of the highest costs. As a result, LTOs are particularly favourable in Europe.

Figure 9. Sensitivity of the LCOE of new build and LTO to capacity factor



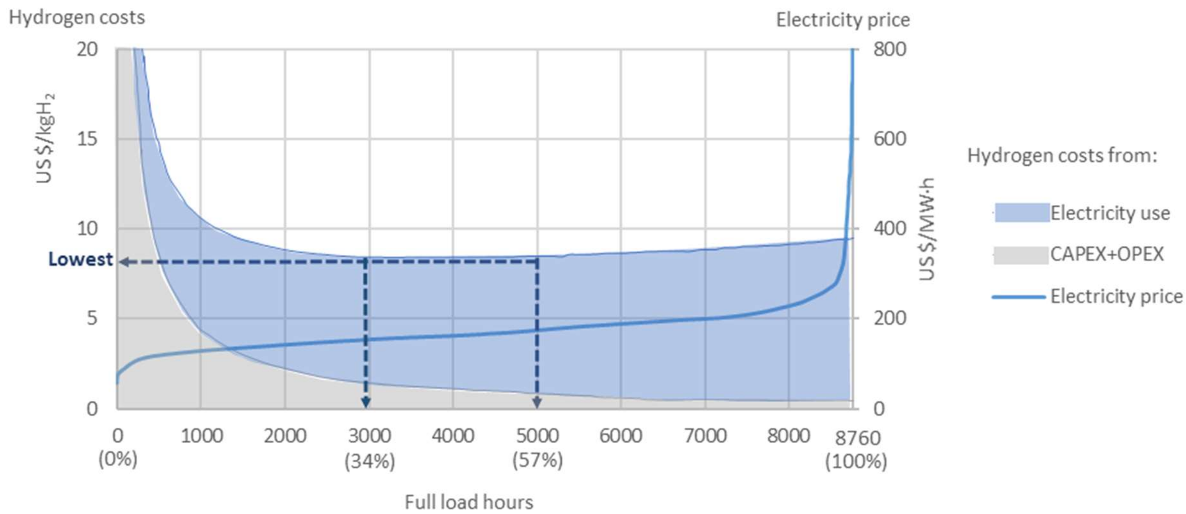
Source: adapted from Ref. IEA & NEA [2020].

Investments in lifetime extensions for required upgrades and equipment replacement have been shown to be the most cost-effective solution for the continued production of nuclear power.

As shown in Figure 7 on page 10, the cost of renewable electricity is assumed to be \$25–73/MW·h, therefore hydrogen production from nuclear power at between \$30-70/ MW·h is a cost competitive means for hydrogen production. However, if the LCOE of new nuclear capacity is much higher than \$70/MW·h then nuclear is no longer competitive for electricity and hydrogen production.

The United States Department of Energy (DOE) has launched the Hydrogen Shot initiative, to achieve a clean hydrogen production cost of \$1/kg by 2031. This ambitious target is equivalent to an electricity price of

Figure 10. Hydrogen costs from electrolysis using grid electricity



Note: CAPEX = USA \$800/kWe; efficiency (LHV) = 64%; discount rate = 8%.
Source: adapted from Ref. IEA [2019].

$20/MW·h aside from capital expenditure (CAPEX) or operational expenditure (OPEX) [Satyapal, 2021]. The current cost of clean hydrogen in the United States is approximately $5/kg or up to $12/kg when delivery and fuelling stations are accounted for.

For hydrogen production from nuclear power to achieve such an ambitious hydrogen cost target, further cost reductions, for example in the case of NPPs in LTO, would need to be promoted. The cost of LTO differs from new construction in that operation and maintenance (O&M) accounts for a large proportion of LTO cost. It is therefore important to reduce the cost of O&M, as well as that of investment.

(c) Capacity factor

The potential exists to use the surplus electricity in power systems with an increasing share of variable renewable energy to produce low cost and low carbon hydrogen. However, if this surplus power is only available occasionally, it cannot be reliably depended upon for production. Figure 10 [IEA, 2019], on the previous page, shows that the longer the electrolyser runs, the greater the impact on the cost of electricity and the lesser the impact of CAPEX on the levelized cost of hydrogen. It is therefore essential to minimize the cost of hydrogen production by achieving an optimal annual level of operating hours to balance this trade-off. If we consider the IEA assumption [IEA, 2019], the area of lowest hydrogen costs can be found when operating an electrolyser for 3000 to 5000 hours in a year, which is equivalent to a capacity factor of 34–57%. Since inexpensive grid electricity may only be available for a few hours during the day on a high renewable penetration grid, the utilization rate of the electrolyser will be low and the hydrogen cost will be high, reflecting the high CAPEX that is spread across only a handful of hours. However, it should be noted that a higher number of utilization hours increases the demand for electricity, producing higher electricity costs. Over time, the cost of producing hydrogen rises due to higher electricity prices during peak hours.

Maximizing surplus output

There are various methods of producing hydrogen, using fossil fuels, renewable energy or nuclear power, with each having its own advantages and disadvantages. While these methods may appear to compete, in reality, they complement one another. Each technology will play a vital role in the transition to achieve carbon neutrality by 2050. Hydrogen production from existing nuclear power is not an exception, it is vital to utilize a wide array of production methods.

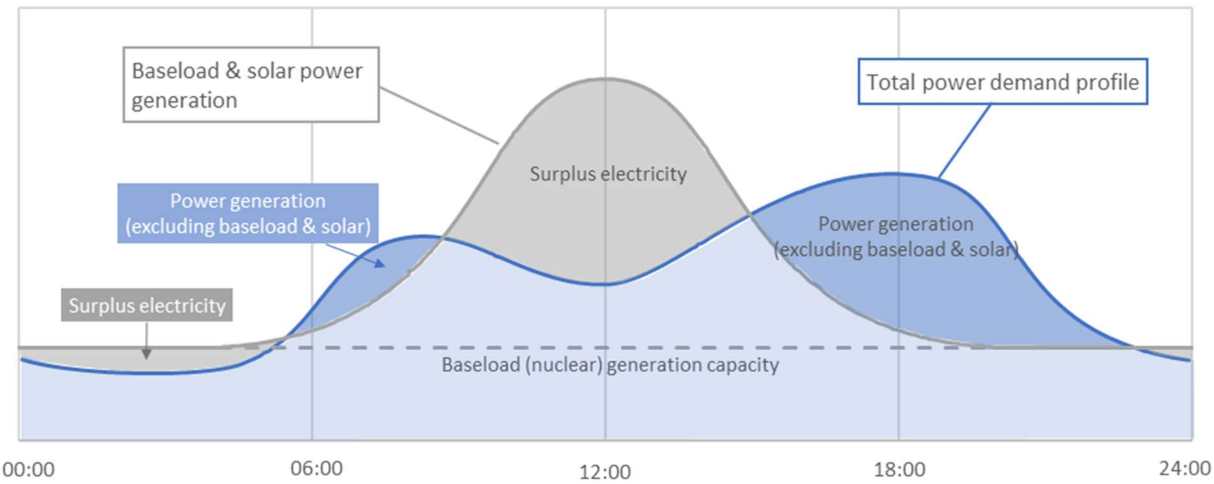
Nuclear power has the advantage of producing electricity in a stable manner, which is useful for continuous hydrogen production and for increasing the capacity factor of the electrolyser. As shown in Figure 11 [INL, 2017], using nuclear power during the night, when both demand and electricity prices are low, would be another advantage since the surplus electricity from nuclear power that is used as baseload power could be used to produce hydrogen. Conversely, at midday, when solar power output is high, surplus electricity could also be used to produce hydrogen. By using a combination of renewable energy and nuclear power in this way, it is also possible to boost the electrolyser utilization rate and minimize hydrogen production costs.

Demand and market conditions

Hydrogen demand

At present, the demand for hydrogen is much smaller than the demand expected in 2050 since it is limited to

Figure 11. Daily generation supply and demand curve



Note: The data used for this figure represents notional power demand and supply curves in summer with high penetration of solar power, where baseload capacity is 60% of total daily demand and solar capacity is 45% of total daily demand.
Source: adapted from Ref. INL [2017].

a few industrial sectors, such as the refining and chemical sectors [IEA, 2021c]. Even in sectors such as transport, steel manufacturing and power generation, where demand is expected to grow significantly over the coming decades, rapid increases in hydrogen demand are not anticipated in the near future (IEA, 2024). To create a decarbonized economy, it will nevertheless be vital to both, replace existing cases of hydrogen use with low carbon hydrogen, and focus on expanding hydrogen use to new sectors. Figure 12 [ETC, 2021] splits the potential uses of hydrogen in a carbon neutral economy into four categories, depending on the ease of introducing hydrogen utilization into existing systems.

Potential hydrogen demand can be broadly categorized into expansion of existing use cases and new use cases. New hydrogen use cases can be further subdivided into transitional opportunities, demand expected in the distant future, and potential demand for hydrogen in the distant future.

Existing use cases include crude oil refining, ammonia production for fertilizer, and methanol production for a variety of products such as paints, plastics and explosives. Most of these cases use hydrogen produced from fossil fuels, which can be replaced with low carbon hydrogen to reduce CO_2 emissions. This is a high certainty demand that low carbon hydrogen producers could initially consider targeting.

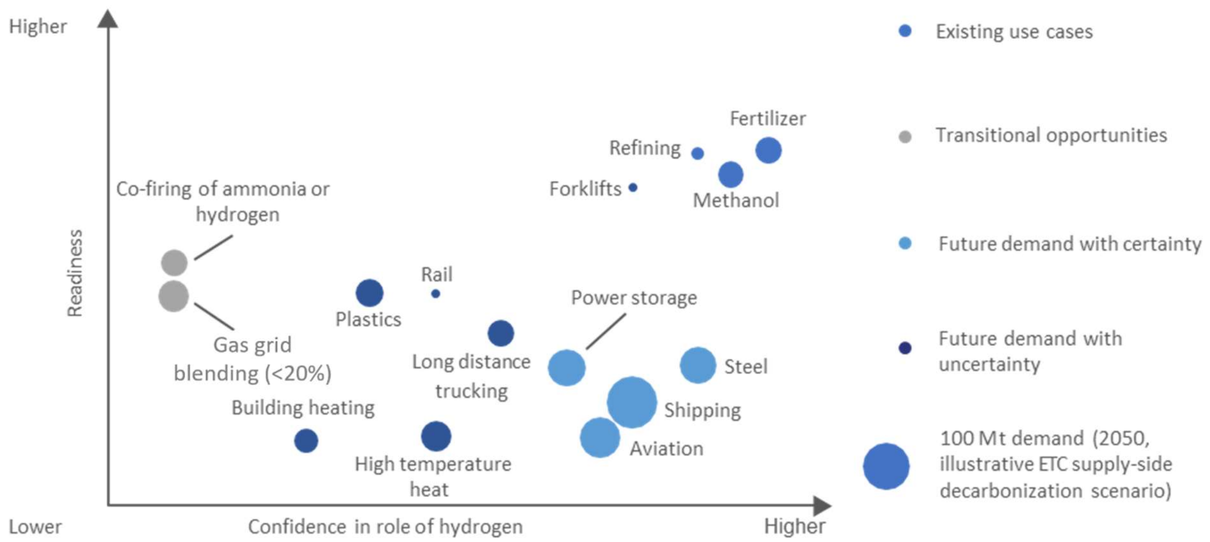
Transitional opportunities include co-firing hydrogen in gas power plants, co-firing ammonia in coal power plants and blending low levels of hydrogen into existing natural gas pipelines. Several countries have already begun pilots which blend hydrogen into natural gas to reduce carbon emissions. For example, the United Kingdom completed a trial project in 2021, where 20% hydrogen was blended into the natural gas supply for 100 homes and 30 university buildings for 18 months (HyDeploy, 2021). The trial successfully showed that hydrogen blending is a viable method of reducing CO_2 emissions using existing infrastructure and appliances. In the future, if the amount of hydrogen in a blended gas exceeds 20%, modifications may need to be made to infrastructure and appliances.

However, while these technologies are expected to reduce CO_2 emissions, they cannot eliminate them. Such opportunities are therefore considered as short term and transitional until 100% hydrogen or ammonia power generation can be established, and natural gas is replaced by hydrogen.

Expected future demand includes steel production, long-distance shipping, long-distance aviation and power storage. These industries are difficult to electrify and commonly referred to as hard-to-abate sectors, making hydrogen or hydrogen-based fuels essential for cost effective decarbonization. Apart from power storage and direct reduced iron with CCS for steel production, there are currently very few alternatives to hydrogen to decarbonize these sectors. As a result, there is high certainty of demand in these sectors, and rapid technological development is underway. It is therefore important to keep a close eye on these sectors.

Potential future demand includes fuel cell transport, such as long-distance trucking, rail and forklifts, building heating, high temperature heat in industrial applications, and plastics and other chemical production. Hydrogen is being considered for use in the decarbonization of these sectors, but it is not necessarily considered superior or cheaper to electrification or other options. With advancements in energy density of batteries, it is likely that electric vehicles will be used for long-distance trucking, instead of fuel cell vehicles. For heating, the most efficient way to provide building heating is by heat pumps, therefore this limits the use of hydrogen for this application.

Figure 12. Potential use cases of hydrogen



Source: adapted from Ref. IAEA [2021a].

Demand for hydrogen in plastic production is uncertain because of the increasing number of alternative materials to replace plastics, and because CO_2 is required in addition to hydrogen. Due to better alternatives or limitations of hydrogen for these applications, it is not clear at this time whether hydrogen demand will increase in such cases.

Using hydrogen clusters to boost initial hydrogen demand

Hydrogen is already used widely in the refining and chemical industries but has yet to advance into other industries. To stimulate market demand, hydrogen clusters are being developed in an effort to integrate hydrogen production, storage, transport and end use in various cases.

The potential for hydrogen clusters will depend on regional demand and geographical differences. In general, however, a focus on cluster-based development can provide hydrogen producers with greater certainty of local hydrogen demand, allowing them to de-risk their business cases by diversifying off takers. Within a cluster, it is relatively easy to expand beyond hydrogen to other valuable high-end products, for example, by supporting the simultaneous development of several new end use applications. Furthermore, clusters can minimize the initial need for investment costs to share large-scale transport and storage infrastructure among several users. Finally, clusters are expected to, and have begun to, receive public support in the funding and licensing of developments that will benefit several companies and sectors.

Various types of hydrogen clusters are being envisioned, with the ETC identifying four of these cluster types [ETC, 2021].

Refining and fertilizer clusters are currently the most hydrogen intensive industries. Since these sectors share gas supply systems and exchange intermediate products, plants are frequently co-located. Several projects using hydrogen produced from renewable energy have been initiated, but most of them are being pursued independently. These projects, nonetheless, have the potential to develop into cluster projects involving neighbouring facilities in the near future.

Port clusters, as logistics hubs, have enormous potential for hydrogen use in transport. Several hydrogen cluster projects have already been launched, exploring the use of hydrogen not only in shipping but also for trucks and forklifts. In addition, ports are often located close to heavy industry sites, such as steel plants and petrochemical plants, and therefore hydrogen is expected to be used throughout these industries.

City clusters serve as non-coastal transport hubs and provide well connected gas pipeline infrastructures. Demand from road transport and heating buildings could therefore develop as a result. This type of cluster has the potential to have a large demand, and some feasibility studies are currently underway.

Steel plant clusters have the potential to have a large hydrogen demand, because the plant itself will require a large and stable amount of hydrogen. Steel plants are often in coastal areas, so these clusters are likely to be developed as part of larger port clusters.

Opportunities for growth

Many of the cluster types mentioned above can benefit from existing NPPs across the world. In the UK, where there are many hydrogen projects, often NPPs are located adjacent to hydrogen projects. Also, in countries with many NPPs, such as France, several hydrogen projects are located next to NPPs. The same is true in the USA, as since 2022, many more hydrogen projects have been initiated in the east of the USA, in closer proximity to the majority of NPPs in the country. Of the seven hydrogen hubs selected for financial support from the United States government, the Midwest, Mid-Atlantic and Heartland hydrogen hubs, will use nuclear power to produce hydrogen. As the number of hydrogen projects increases in future, it is expected that more projects will be undertaken in very close vicinity to existing NPPs, with geographical advantages offering cost optimization through the formation of hydrogen clusters that include NPPs.

On the other hand, from the outset of a project, more efforts are being made to utilize electricity from NPPs to promote efficient hydrogen production. In the UK and the Russian Federation, hydrogen cluster projects using NPPs to support facilities for hydrogen hubs have been proposed. Hydrogen hubs will create networks of hydrogen producers, consumers and local connective infrastructure to accelerate the use of low carbon hydrogen produced from renewable energy and nuclear power [US DOE, 2022]. Hydrogen clusters using nuclear energy are therefore gradually expanding around the world.

Publicly funded support

In 2024, the EU Hydrogen Bank (European Commission, 2024a) conducted the first auction of renewable hydrogen. The bidders applied for incentives from an 800-million-euro Innovation Fund Auction Budget to back up their hydrogen production projects produced from renewable energy. The levelized cost of hydrogen varied by country, with a minimum of €5.3/kg in Greece to €13.5/kg in Poland, pricing far above the price of hydrogen produced from fossil fuels, which is approximately €2/kg. The countries with the lowest prices had the highest load factors, particularly solar energy in southern Europe and countries with lots of hydropower, such as Sweden. Even if the price of carbon, which at €65/tonne and assuming 10 kg of CO_2 per kg of hydrogen, is added to the fossil fuel production price, the price reaches €2.65/kg, far below that of renewable hydrogen projects. Although the projects in the first Hydrogen Bank auction were subsidised, buyers still paid a premium to buy hydrogen produced from renewable energy.

This EU Hydrogen Auction on incentives might be considered as a response to the USA IRA with incentives up to 3$/kg H2 (see USA hydrogen policy on page 5).

3. Utility demonstration projects

Key points:

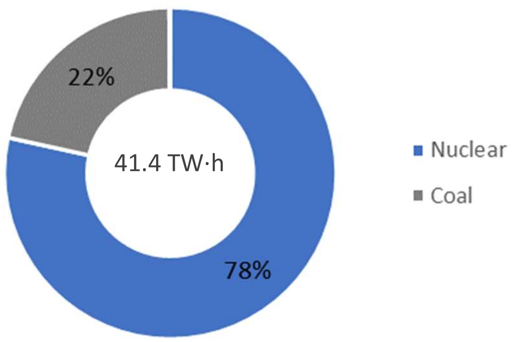
- In recent years, small scale hydrogen production projects using electricity from existing NPPs have been initiated around the world to demonstrate their technical feasibility and economic competitiveness.
- Nuclear hydrogen projects are underway, but only one NPP in the USA which didn't produce hydrogen in its initial design, is now producing hydrogen. Many projects are under construction or in the feasibility stages.
- By producing low carbon hydrogen, utilities are contributing to the realization of a decarbonized society, as well as gaining an additional revenue stream from surplus electricity.

An overview of demonstration projects

Progress with nuclear hydrogen demonstration projects varies globally depending on each region. Since the publication of this booklet in January 2023, two projects—Energy Harbor and Arizona Public Service—have been discontinued, with details of both of these projects included as lessons learnt. Meanwhile, new nuclear hydrogen demonstration projects have commenced, particularly in Asia, including initiatives in The Republic of Korea and Japan. Selected nuclear hydrogen demonstration projects from around the world are outlined in the following paragraphs.

Energy Harbor (USA)

Figure 13. Energy Harbor generation in 2019



Source: based on data from Ref. Government of USA [2019].

NPP:	Davis-Besse Nuclear Power Plant PWR (894 MWe)
Location:	Oak Harbor, Ohio, USA
Electrolyser:	LTE PEM (2 MWe)

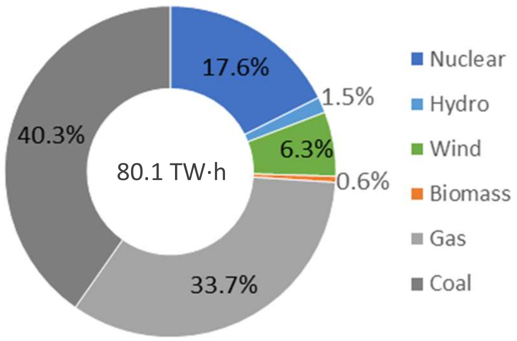
Energy Harbor in the USA operated 3947 megawatt electric (MWe) of nuclear power capacity (comprising four reactors at three sites in the country), supplying about 32.4 terawatt hours (TW·h) of low carbon electricity from NPPs annually, as shown in Figure 13. In March 2024, Energy Harbor was acquired by Vistra Corporation. In 2019, Energy Harbor was part of a consortium of companies — which included Xcel Energy and Arizona Public Service — that was selected to receive a grant from the DOE in the framework of the Advanced Reactor Development Project funding pathway [INL, 2019; US NE, 2019]. This project met the DOE objective to support innovation in and the competitiveness of the USA nuclear industry through research, development and demonstration of commercial applications that pair carbon free nuclear energy in a hybrid, non-electric application to produce hydrogen.

Energy Harbor planned a two year demonstration project at the Davis-Besse NPP in Ohio, where the company planned to install a 2MW LTE skid to produce hydrogen. The demonstration project was expected to begin hydrogen production from nuclear power in 2024. The selected LTE was a PEM electrolyser, which would consume electricity from the NPP and produce 800–1000 kg/day H_2. Energy Harbor's objective was to explore the economic viability of hydrogen production in the NPP, and to demonstrate the compatibility and synergy of the two technologies. Potential uses of the hydrogen included public transport and steel production. The NPP is located near major hydrogen markets, such as oil refineries and steel manufacturers, making it ideal for reducing hydrogen transport costs. In 2022, the company joined with these regional hydrogen related companies, the University of Toledo and several national laboratories, as well as others, to launch a new industry led coalition, called Great Lakes Clean Hydrogen (GLCH) [Energy Harbor, 2022a].

In 2023 the DOE selected regional hubs for hydrogen production, but the DOE did not select GLCH as a hydrogen hub. All selected projects benefitted from a shared $7 billion investment from the DOE, however without DOE support the Davis-Besse hydrogen project was deemed uneconomical and has been scrapped.

Xcel Energy (USA)

Figure 14. Xcel Energy generation in 2019



Source: based on data from Ref. Government of USA [2019].

NPP:	Prairie Island Nuclear Generating Plant PWR (1041 MW)
Location:	Welch, Minnesota, USA
Electrolyser:	HTE (240 kW, maximum 1 MW)

Xcel Energy in the USA has set a target of delivering 100% carbon free electricity by 2050, and as Figure 14 shows, in addition to increased wind power and reduced fossil fuel use, stable nuclear power operation has contributed to reductions in carbon in recent years. Xcel Energy's hydrogen production demonstration project will use high temperature steam electrolysis (HTSE) SOEC, utilizing steam and electricity from the Prairie Island NPP in Minnesota. Water will be converted into hydrogen at elevated temperatures, therefore producing hydrogen more efficiently than low temperature methods such as PEM or alkaline hydrolysis.

Since Xcel Energy has several wind power facilities in its energy generation portfolio, it typically curtails nuclear power when wind power is able to meet electricity demand [Xcel Energy, 2022]. Rather than curtailing nuclear power in low or negatively priced hours, Xcel Energy is evaluating opportunities to produce hydrogen from surplus nuclear power. If this excess electricity can be used to produce hydrogen, it has the potential to create an additional revenue stream that will help cover fixed costs.

In this project, the 240 kW electrolyser (moving towards a maximum of 1 MW in the future) will produce about 130 kg/day H_2. Because the project size is smaller than the curtailment increment, the electrolyser will be able to run continuously, independent of nuclear curtailment resulting from variable wind generation. Due to the project's small scale, the cost to compress, store and ship the hydrogen may not offset savings from hydrogen use. However, given the location of the NPP, if the scale of production is expanded, hydrogen could be used in a variety of nearby industries, including oil and gas production and agricultural ammonia manufacturing, as well as transport and power generation.

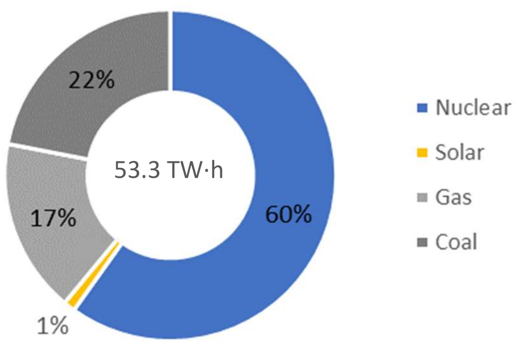
Xcel Energy conducted a technoeconomic analysis with Idaho National Laboratory (INL), the Argonne National Laboratory (ANL) and the National Renewable Energy Laboratory (NREL) and the Electric Power Research Institute (EPRI) of the potential hydrogen demand around NPPs and of optimal hydrogen production with high temperature steam electrolysis using electricity from NPPs [INL, ANL, NREL, EPRI, Xcel Energy, 2021]. Xcel Energy have challenging emissions targets for the region surrounding the Prairie Island and Monticello NPPs and the technoeconomic study aimed to identify the size of the hydrogen market under the assumption of reaching those targets. It also identified the target electricity price for hydrogen produced for the project, to be competitive with SMR. The study identified that a large CO_2 credit would be required given the unlikelihood of significant reductions in NPPs O&M costs. Additionally, the analysis considers the optimal combination of HTE capital expenses, HTE capacity and a possible hydrogen production tax credit to ensure profitability compared to a business-as-usual case. The analysis also notes the importance of identifying hydrogen demands, along with the delivery requirements, that will drive the availability of hydrogen storage and the overall project costs.

In 2020, the DOE provided approximately $14 million in funding for the project [INL, 2020; US NE, 2020], which was expected to begin hydrogen production at the start of 2024. Xcel Energy did propose two hydrogen hubs to the DOE; however, the Prairie Island project was not included as one of these proposed hydrogen hubs so has not benefitted from the shared $7 billion subsidy from the DOE. As of January 2025, it is unclear whether the Prairie Island project is still being pursued.

In 2023, Xcel Energy and partners proposal for the Heartlands Hub was selected as one of seven hydrogen hubs by the DOE (Office of Clean Energy Demonstrations, 2023). Xcel Energy are set to receive a large share of the funding, subject to ongoing negotiations, with detailed design of the hub yet to be announced. The hub is a long-term project, with project development likely to continue through 2035.

APS and PNW Hydrogen (USA)

Figure 15. APS generation in 2019



Source: based on data from Ref. Government of USA [2019].

NPP:	Palo Verde Nuclear Generating Station PWR (3937 MW)
Location:	Wintersburg, Arizona, USA
Electrolyser:	LTE PEM (17 MW)

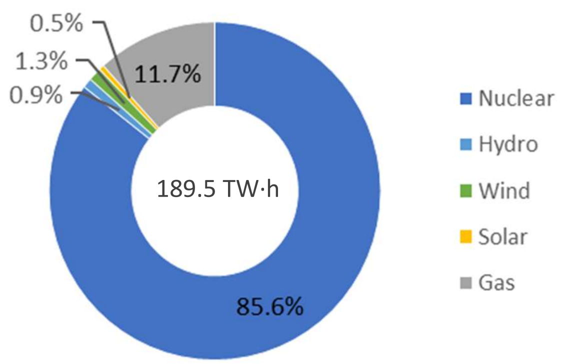
Arizona Public Service (APS), main subsidiary of Pinnacle West Capital Corporation (PNW), has also set a goal to provide carbon free electricity by 2050. The Palo Verde NPP, which is mainly operated by APS, is the largest plant in the country. As can be seen in Figure 15, it generates more than 31.9 TW·h annually, contributing to a substantial proportion of APS's clean energy production. In 2021, APS conducted a technoeconomic assessment of the use of hydrogen, produced with electricity generated by its Palo Verde NPP, as an energy storage medium to help run the natural gas fired combustion turbines used to meet peak electricity loads. The assessment showed that the capacity cost from co-firing hydrogen in a peaking natural gas fired turbine compared favourably to the capacity cost from batteries when the energy storage duration is four hours or more.

Based on the results of the assessment and building upon its collaboration with consortium members (Energy Harbor and Xcel Energy) PNW Hydrogen, a subsidiary of PNW, submitted an application to the DOE for funding to run a three-year nuclear-to-hydrogen-to-electricity demonstration project beginning in 2022. The size of the electrolyser was expected to be approximately 17 MW and a compression and storage system was also intended to be installed. PNW Hydrogen was seeking to use surplus nuclear energy during hours when renewable production is high, or when electricity demand is low for hydrogen production. The produced and stored hydrogen was then intended to be used to produce electricity during times when solar energy resources are not available and energy reserves are low. The final objectives of the demonstration project were to co-fire a 30%/70% (or greater) hydrogen/natural gas blend in the APS Saguaro gas fired peaking power plant and use a small quantity of the hydrogen to produce synthetic hydrocarbons. On 7 October 2021, the DOE notified PNW Hydrogen that its application regarding this first of a kind project had been accepted and awarded $20 million, which is approximately 25% of the total project cost [US DOE, 2021].

The aim of APS was to produce hydrogen for energy storage, to account for times when there is reduced solar generation. However, in May 2023 the project was suspended, as it was deemed 'economically unfeasible' as the final cost of the hydrogen was determined to be too expensive to be cost competitive.

Constellation Energy (USA)

Figure 16. Constellation Energy generation in 2019



Source: based on data from Ref. Exelon [2020].

NPP:	Nine Mile Point Nuclear Station BWR (1890 MW)
Location:	Scriba, New York, USA
Electrolyser:	LTE PEM (1.25 MW)

Constellation Energy (formerly Exelon's power generation business) is one of the main NPP operators in the USA. As shown in Figure 16, nearly 90% of annual electricity output produced by Constellation Energy comes from nuclear and renewable energy. Constellation Energy operates 21 reactors at 12 facilities across Illinois, Maryland, New York and Pennsylvania. Constellation Energy planned to demonstrate the production, storage and use of hydrogen at an existing NPP. Due to the company's extensive nuclear portfolio, site selection was identified as one of the most important challenges for the demonstration project. In 2021, Constellation Energy chose the Nine Mile Point NPP as the site for the demonstration project, based on technical and business factors [Exelon, 2021b]. Technical factors include the site's electrical, mechanical and land constraints, and hydrogen consumption, as well as water availability. Business factors include the price of hydrogen, the electricity price and agreements with state and market operators. The company has recognized in particular the strong support for hydrogen provided through the New York Clean Energy Standard, which has set a goal of 50% clean energy consumption in the state of New York by 2030.

The Nine Mile Point project began in 2020 and had a project duration of three years (becoming operational by the end of 2022), with a budget of $14.4 million. The project received $5.8 million in funding as part of the DOE H2@Scale award to support the construction and installation of the electrolysis system. The plant began generating hydrogen in March 2023, only a few months after planned production, and the project was completed on budget (Constellation Energy, 2023).

The project is a collaboration between Constellation Energy, NREL, Nel Hydrogen (a Norwegian Nel ASA subsidiary), INL and ANL. Nel Hydrogen provided the 1.25 MW PEM electrolyser for the project which was installed on-site. The plant can produce 531 kg of hydrogen per day, with approximately 15% of production used as a cooling gas for the plant's generator in order to reduce the O&M costs of the plant and ensure chemistry control for the plant components. Constellation Energy are exploring dynamic operation of the site, aiming to find an optimal balance between economics and operating conditions for long-term operation.

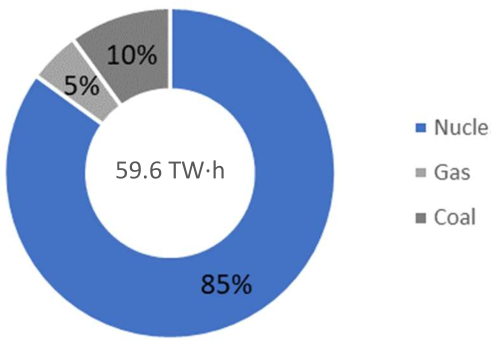
Following the success of the pilot plant, an additional $12.5 million has been awarded by the New York State Energy Research and Development Authority (NYSERDA), to install a fuel cell at the facility. The follow-on project is expected to begin operation in 2025 and could allow excess capacity from the electrolyser to be stored and released into the grid at times of peak demand (Constellation Energy, 2023). Other future applications for the hydrogen include on-site vehicles, such as forklift or delivery trucks, which could either use the hydrogen directly or through the fuel cell equipment. The wider hydrogen market demand potential was also calculated by ANL for nine other generating stations in the vicinity of the plant, to determine the near-term and long-term demand at areas of opportunity such as, refinery operations, ammonia production, synthetic fuels and direct reduction of iron ore.

Due to the success of the pilot plant, Constellation Energy applied for further DOE funding to develop a larger plant at the LaSalle NPP. In October 2023 Constellation Energy were selected as part of the Midwest Alliance for Clean Hydrogen (MachH2) hub, one of seven hydrogen hubs allocated up to $7 billion, in total, from the Inflation Reduction Act. The clean hydrogen facility at LaSalle is estimated to cost $900 million, with a portion of the MachH2 funding offsetting the total project cost.

EDF Energy (United Kingdom)

EDF Energy generates low carbon electricity from wind, solar and nuclear sources. As shown in Figure 17, nuclear energy accounts for more than 80% of the company's annual generation. The utility conducted a feasibility study for the production of hydrogen from nuclear power at the Heysham Power Station, and it is preparing a demonstration project at the Sizewell Power Station.

Figure 17. EDF Energy generation in 2019



Source: based on data from Ref. EDF [2020].

Heysham Power Station

NPP:	Heysham Power Station AGR (2300 MW)
Location:	Morecambe, Lancashire, UK
Electrolyser:	LTE alkaline (1 MW) + PEM (1 MW) 2019 SOEC (1 MW) 2023

EDF Energy received funding from the UK government in 2019 to carry out a pilot hydrogen production project at the Heysham NPP in the first step towards large scale low carbon hydrogen production [EDF Energy, 2019]. In Phase 1, the utility worked with Lancaster University, the European Institute for Energy Research (EIFER) and the AtkinsRéalis to conduct a feasibility study for low carbon hydrogen production with the direct installation of a 1 MW PEM electrolyser and a 1 MW alkaline electrolyser to produce up to 800 kg/day H_2 at the Heysham NPP.

It was concluded that the system should be installed outside of the nuclear licence area for security and operational efficiency reasons and that the conceptional design met the requirements of nuclear safety and industrial regulations. Although the project was technically feasible, it did not progress any further as the levelized cost of hydrogen calculated to be between £6.73-£8.60/kg, which was deemed to be economically unfeasible without production subsidies or incentives for end users [Nuclear Industry Association, 2021].

However, in March 2023 a new feasibility study was conducted to produce hydrogen at Heysham (Department for Energy Security and Net Zero, 2023). The key differences with this study were that a 1 MW SOEC was selected instead of LTE electrolysers, and that the project is part of a wider Bay Hydrogen Hub which will support the decarbonisation of asphalt and cement. The use of SOEC technology aims to improve the efficiency of hydrogen production by 20% compared to PEM, therefore improving the economic viability of the project.

In September 2023 the Department for Energy Security and Net Zero awarded £6.1 million to develop the Bay Hydrogen Hub-Hydrogen4Hanson project, as part of the UK Government's £1 billion Net Zero Innovation Portfolio (Department for Energy Security & Net Zero, 2023a). The Bay Hydrogen Hub is owned by EDF Energy Nuclear Generation Ltd, in collaboration with Hanson UK, National Nuclear Laboratory Ltd, EDF Energy R&D UK Centre Ltd and Asphalt Burner Services Ltd and FuelCell Energy have been contracted to produce the SOEC technology for project.

The main aims for the Bay Hydrogen Hub are to demonstrate the use of SOEC integration using heat from Heysham as feedstock to produce hydrogen; investigate transport of hydrogen without using a pipe network and to be a FOAK plant to demonstrate decarbonisation of asphalt production using hydrogen as a fuel. The demonstration is set to begin in 2025.

Sizewell power stations

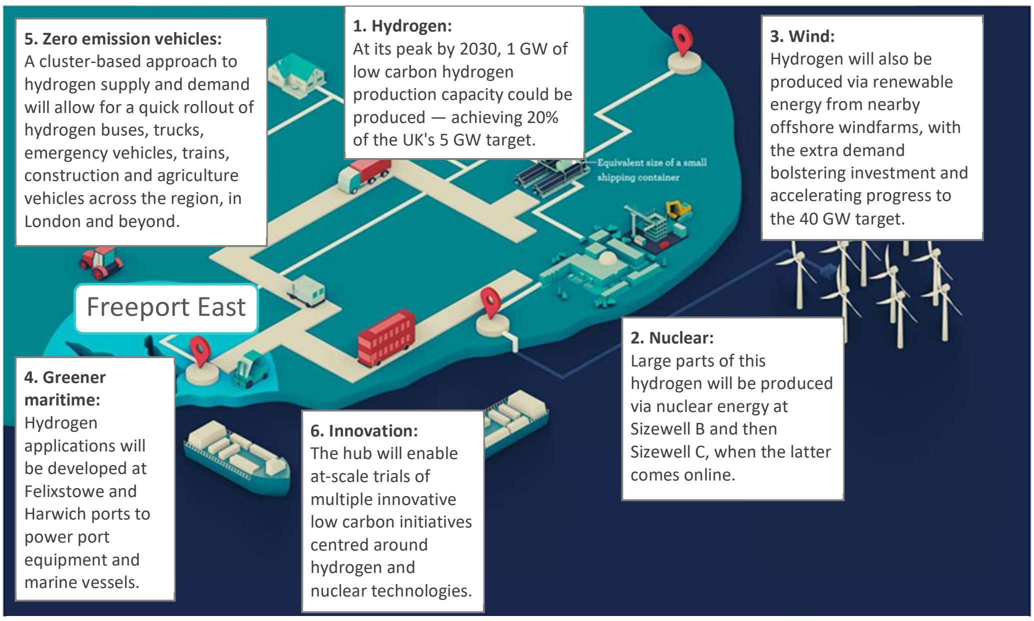
NPP:	Sizewell B Power Station
	PWR (1198 MW)
Location:	Leiston, Suffolk, UK
Electrolyser:	LTE (2 MW)

EDF Energy has been exploring hydrogen production at the site of the Sizewell B NPP to help contribute to the net zero ambitions of the UK [EDF Energy, 2022]. Specifically, the utility planned to install a 2 MW electrolyser and begin producing up to 800 kg/day H_2 using electricity from the Sizewell B NPP [EDF Energy, 2020]. The hydrogen produced will be used to fuel some of the vehicles and machinery that are to be operated during the construction of the Sizewell C NPP, reducing the use of diesel fuel. However, since 2022 there have been no further developments to produce hydrogen at Sizewell B.

Plans are in place to build Sizewell C, a 3200 MW European pressurized water reactor (EPR), next to Sizewell B, with a final investment decision to be made at the end of 2024. In September 2023 a deal was signed with Wrightbus to order four hydrogen buses as a pilot to test whether hydrogen buses could be used during the construction of Sizewell C. If the scheme is successful, then 150 buses will be ordered to transport workers around the construction site (Wrightbus, 2023).

There is potential for Sizewell C to produce: hydrogen to power vehicles, machinery during construction, fuel up to 150 onsite hydrogen buses, contribute to a local refuelling and maintenance hub, sustainable aviation fuel alongside CO_2 captured through direct air capture (SizewellC, 2023). Both Sizewell NPPs will be part of Freeport East, with the plan for the NPPs to produce a

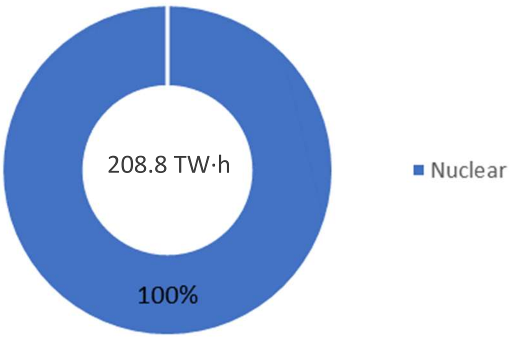
Figure 18. Freeport East Hydrogen Hub



Source: adapted from Ref. (Freeport East, 2022) large part of the 1 GW of hydrogen production at the port, with the rest of the hydrogen produced from nearby offshore windfarms (Freeport East, 2022).

Rosatom (Russian Federation)

Figure 19. Rosatom generation in 2019



Source: based on data from Ref. Rosatom [2022].

NPP:	Kola Nuclear Power Plant VVER (1644 MW)
Location:	Polyarnyye Zori, Murmansk, Russian Federation
Electrolyser:	LTE PEM (1 MW)

As shown in Figure 19, Rosatom generates about 200 TW·h of nuclear power, representing around 20% of the total power generated in Russia. Rosatom has been carrying out extensive research on hydrogen production since 2018, with priority given to the development of water electrolysis using existing NPPs, as well as SMR using a HTGR.

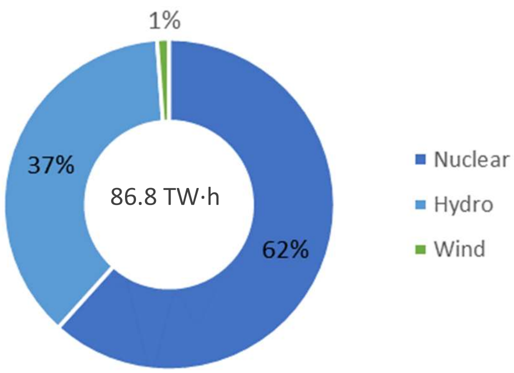
In 2020 the Development of Hydrogen Energy in the Russian Federation until 2024 plan [Government of Russian Federation, 2020a] was established and in 2021 the Concept for the development of hydrogen energy in the Russian Federation [Government of Russian Federation, 2021]. The former includes an evaluation of regulations related to nuclear hydrogen by 2022, the development of a safety concept for hydrogen production, transport and storage by 2023, and the development of a programme for nuclear energy technologies applicable to hydrogen energy projects by 2024. The latter assumes the development of hydrogen over three phases with the first phase (2021 to 2024) establishing hydrogen clusters, such as the West hydrogen cluster, which will include the Kola NPP [Rosatom, 2021b]. The hydrogen produced in these clusters was not only to be used to decarbonize domestic industry, transport and energy sectors, but it was also planned to be exported to Europe from the West hydrogen cluster and to the Asia-Pacific region from the East hydrogen cluster.

Kola NPP was selected for a pilot hydrogen production project, partly as the plant produces surplus electricity which can be used to produce the hydrogen and partly as the NPP already produced small quantities of hydrogen through alkaline electrolysis, to cool its own turbogenerators. In December 2022, Kola NPP began producing hydrogen through PEM electrolysis. A 1 MW PEM electrolysis unit was installed, with plans to scale the unit's capacity to 10 MW to increase hydrogen production. As of December 2023, there are plans to launch the bench test facility of Kola NPP by 2025, depending on the outcome of an ongoing environmental assessment, producing up to 150 tonnes of hydrogen per year (HydrogenWire, 2024).

In 2020, the Russian Federation planned to increase low carbon hydrogen exports to 0.2 million tonnes by 2024 and to 20 million tonnes by 2035 [Government of Russian Federation, 2020b]. However, in December 2023 the Director of Kola NPP noted that there is uncertainty around hydrogen projects as exports are currently not possible, therefore there are questions whether a planned facility, will be built at Kola NPP by 2025 (Interfax, 2024) .

Vattenfall (Sweden)

Figure 20. Vattenfall generation in Sweden in 2019



Source: based on data from Ref. Vattenfall [2020a]

NPP:	Ringhals Nuclear Power Plant PWR (2202 MW)
Location:	Ringhals, Väröbacka, Sweden
Electrolyser:	LTE (0.8 MW)

Vattenfall owns 5485 MWe of operating capacity (comprising of five reactors at two facilities) located in Sweden. As shown in Figure 20, nuclear generation represented around 62% of Vattenfall's total electricity generation in Sweden in 2019. Vattenfall has been producing hydrogen at the Ringhals NPP since 1997 [Vattenfall, 2018], using a LTE electrolyser which has a 0.8 MW capacity and produces 60–110 m^3/hour H_2. The hydrogen is then used to cool generators at the NPP. Vattenfall does not currently have any plans to expand or develop hydrogen production on-site at the Ringhals and Forsmark NPPs.

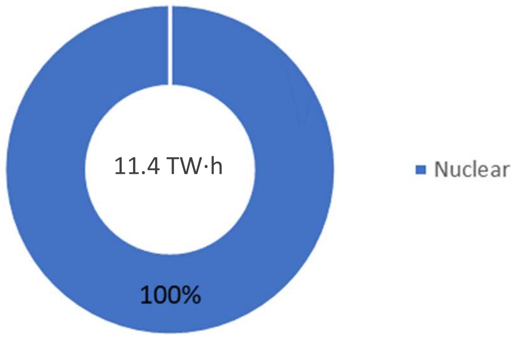
However, Vattenfall is applying this experience in a pilot study with Preem, the largest oil company in Sweden, to produce hydrogen using electricity from the grid [Vattenfall, 2021a]. Vattenfall sells only nuclear, hydro, wind and minimal amounts of biomass electricity in Sweden, so the electricity from the power grid is fossil free. Preem and Vattenfall are testing the use of hydrogen in the production of biofuels using detritus from the Swedish paper industry. Hydrogen reduces the oxygen content of the polymers that make up the plant tissue in the pulp, creating biofuel. A feasibility study for a larger 50 MW electrolyser plant was due to start in 2022, however no further details on the project have been published since 2022.

Vattenfall has also established the Hydrogen Breakthrough Ironmaking Technology (HYBRIT), a joint venture with the Luossavaara-Kiirunavaara AB (LKAB), a mining company, and Svenskt Stål AB (SSAB), a steel manufacturer, which together have been working on a hydrogen-based steelmaking process since 2016 [Vattenfall, 2021b]. The project is targeting completion by 2035 and the pilot plant in Luleå, in northern Sweden, started operation in August 2020. In May 2021, the construction of a 100 m^3 pilot scale storage facility next to the pilot plant, in a cave around 30 metres underground, began [Vattenfall, 2021c] and was completed in June 2022 (Vattenfall, 2022). At the end of 2023 the hydrogen storage facility was tested commercially on the electricity market, with the variable cost of the hydrogen being reduced by between 25 to 40 % by using the hydrogen storage facility (Vattenfall, 2023). At full capacity the storage facility could contain 100,000-200,000 m^3 of hydrogen, enough to power a full-size mill's production for up to four days.

In July 2021, Vattenfall delivered the world's first steel produced using the HYBRIT technology, to the car manufacturer, Volvo. The production process involved the use of 100% fossil free hydrogen, rather than coal and coke, to reduce the iron ore [Vattenfall, 2021d]. Due to the success of the HYBRIT project, in December 2023 the project received a SEK 3.1 billion ($302 million) grant from the Swedish Energy Agency to establish an industrial scale demonstration plant, with a 500 MW electrolyser, in Gällivare, northern Sweden. The demonstration plant is one of 35 projects from EU countries, which allow member states to provide state support to initiatives of strategic European interest. The demonstration plant is scheduled to begin production in 2026, producing approximately 1.2 million tonnes of crude steel annually, with the potential to reduce Sweden's emissions by 14.3 million tonnes over the first ten years of operation (HYBRIT, 2024).

OKG (Sweden)

Figure 21. OKG generation in 2019



Source: based on data from Ref. IAEA [2024]

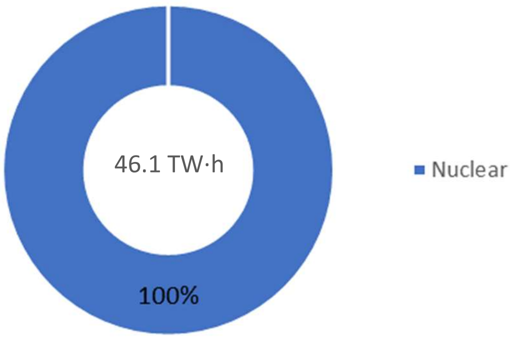
NPP:	Oskarshamn Nuclear Power Plant BWR (1450 MW)
Location:	Simpevarp, Oskarshamn, Sweden
Electrolyser:	LTE alkaline (0.7 MW)

Uniper-owned OKG Aktiebolag (OKG), own only one reactor, but it is one of the world's largest boiling water reactors (BWRs) with a gross output of 1450 MW and generation of 11.4 TW·h of electricity annually in 2019, as shown in Figure 21. At the Oskarshamn NPP, hydrogen is produced using electricity from the NPP and has been used to cool the generators at the NPP since 1992. The 0.7 MW alkaline electrolyser is located next to the plant and has the capacity to produce hydrogen for three NPPs. Since Oskarshamn NPP units 1 and 2 were shut down permanently in 2013 and 2017, and only unit 3 is in operation, the hydrogen plant has some overcapacity. Although the excess amount of hydrogen produced from Oskarshamn is relatively small, the company expects the demand for hydrogen to increase in the future and is considering expanding the hydrogen plant. In view of the importance of maximizing the use of hydrogen facilities already in place, modernization and replacement of the equipment, including the control system, has been carried out.

In 2022, OKG became the first in the world to sign a contract for the supply of hydrogen generated from nuclear energy, partnering with industrial gas company Linde Gas [OKG, 2022]. In May 2024, OKG signed a contract with Hynion to supply surplus hydrogen from Oskarshamn NPP to Hynion's hydrogen filling stations (Hynion, 2024).

Bruce Power (Canada)

Figure 22. Bruce Power generation in 2019



Source: based on data from Ref. Bruce Power [2020a].

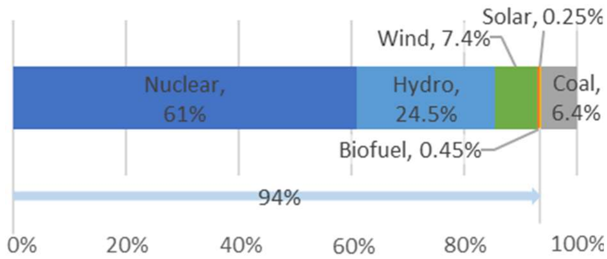
NPP:	Bruce Nuclear Generating Station PHWR (6358 MW)
Location:	Tiverton, Ontario, Canada
Electrolyser:	LTE PEM (5 MW)

Bruce NPP has a total capacity of 6358 MWe (comprising eight reactors) and is one of the largest NPPs in the world. As shown in Figure 22, in 2019 it generated 46.1 TW·h, which is equivalent to half of nuclear generation in the province of Ontario as a baseload supply. However, the plant has a flexible capability, which is also utilized to meet falling and peaking demand in the province.

As a result, more than 90% of Ontario's electricity is generated by nuclear, hydro and renewable energy sources (see Figure 23), and thus Ontario could potentially have a global competitive advantage in producing low carbon hydrogen using electricity. In addition, there is sufficient demand for hydrogen in Ontario from the oil refining and chemical industries, as well as for home heating.

As one of the eight immediate actions included in Ontario's low carbon hydrogen strategy [Ministry of Energy, Ontario, 2022], Bruce Power has a plan to explore opportunities for optimized energy production, including hydrogen production during the night using reactors at the Bruce NPP [Bruce Power, 2022]. A feasibility study was completed in June 2023, in collaboration with British Petroleum New Zealand (BPNZ), Greenfield Global, Hensall Co-op, Hydrogen Optimized, and Hatch to assess the potential development of a nuclear hydrogen hub in the region of Bruce, Grey and Huron counties. The report found that the basic requirements are in place to successfully demonstrate a nuclear hydrogen hub in the region (Bruce Power, 2023).

Figure 23. Ontario's electricity production in 2019

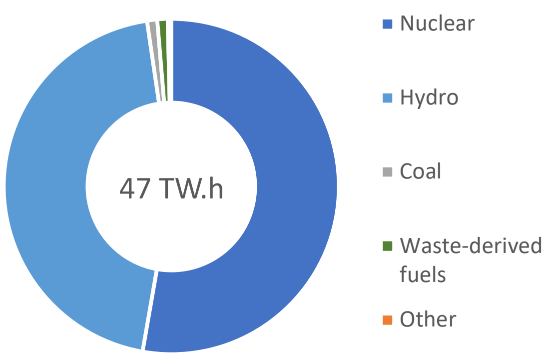


Source: based on data from Ref. Bruce Power [2020a].

In 2023 a new feasibility study by Kinetrics and FuelCell Energy, supported by Bruce Power, was initiated to explore the techno-economic assessment of a hydrogen hub in Toronto (Kinectrics, 2023). The hub would produce hydrogen by SOEC electrolysis, for power generation and a hydrogen fuelling stations for heavy duty vechicles. The project aims to: demonstrate the value of hydrogen as part of the electrical grid, identify any key considerations for deployment, and act as a pilot for larger scale hydrogen systems which include nuclear power. The study was awarded CAD 250,000 in October 2023 and is one of a number of pilot projects funded by Ontario's Energy Ministery and their CAD 15 million Hydrogen Innovation fund.

Fortum (Finland)

Figure 24. Fortum generation in 2023



Source: based on data from Ref. Fortum [2023]

NPP:	Loviisa Nuclear Power Plant PWR (1014 MW)
Location:	Loviisa, Finland
Electrolyser:	Alkaline (1 MW)

Fortum is a Nordic energy company which owns the Loviisa NPP in Finland and co-owns three other NPPs in Finland and Sweden, including Oskarshamn 1. Fortum mainly generates electricty from hydropower and nuclear energy, as can be seen from Figure 24 (Fortum, 2023). The company has been operating the two reactors at Loviisa NPP since they were commissioned in 1977 and 1980.

In 2024 Fortum announced their intentions to build a pilot hydrogen plant at the Kalla test centre, on land close to the Loviisa NPP. The initial intention was to employ an electrolyser capacity of 2 MW, however in June 2024 it was announced that Stargate Hydrogen will be producing a 1 MW alkaline electrolyser for the project (Stargate Hydrogen, 2024). A filling station will be built in connection with the plant for delivering hydrogen to industrial users. The construction of the Kalla test centre is to begin in mid 2024, with operation scheduled for late 2025 to 2028. The entire cost of the project will be covered by Fortum’s R&D budget, with an estimated cost of €17 million. The hydrogen plant will be attached to the grid, rather than directly linked to the Loviisa NPP. In 2023, 42% of the electricity generated in Finland was from nuclear and 52% of the electricity generated was from hydropower, solar, wind and biomass (Finnish Energy, 2024). Although the hydrogen plant is not directly linked to the Loviisa plant, because Finland’s low carbon electricity grid ensures that connecting a hydrogen plant directly to the grid will still enable the production of clean hydrogen.

4. Status of other countries with nuclear power plants

Key points:

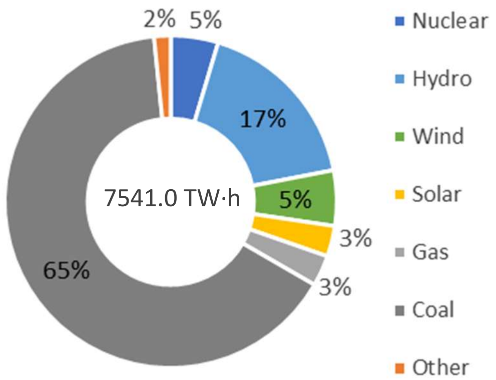
- While there are many existing nuclear power plants in Asian countries, very few have associated hydrogen production projects using the electricity from NPPs. This is primarily due to the dominance of fossil fuels and the relatively small proportion of low carbon energy in their electricity generation mix.
- China and Japan are, nevertheless, actively engaged in R&D for more efficient hydrogen production using electricity and heat, or only heat, from high temperature gas cooled reactors.
- Most recently the Republic of Korea announced ambitions to produce hydrogen at a 10 MW pilot plant from existing nuclear as soon as 2027.

Overview of other countries

Although neither China nor Japan have initiated projects to produce hydrogen with existing NPPs, both countries have started advanced reactor development. Construction of prototype advanced reactors has commenced, with applications beyond the electricity market, such as hydrogen production. Korea, which also has many NPPs, plans to build a 10 MW pilot hydrogen production facility using existing nuclear by 2027. Globally, other countries have expressed an interest in nuclear based hydrogen production, although none have active projects.

China

Figure 25. China generation in 2019



Source: based on data from Ref. IEA [2022].

As of August 2024, China have built over 34 GW of new nuclear power capacity in the last 10 years, with a total of 56 operating nuclear reactors and 29 new reactors under construction (IAEA, 2024). Under the influence of China's zero carbon policy, there has been a large increase in nuclear power capacity and the cost of electricity generation from nuclear power has been reducing. As China's hydrogen industry is not fully mature, and the cost of hydrogen production from nuclear power in China is relatively high compared to other low carbon technologies, therefore it has been more economical to focus on electricity generation from NPPs.

China's state nuclear company, the China National Nuclear Corporation (CNNC), recognizes the importance of producing hydrogen with nuclear power as an energy storage method to help balance the country's power system [CNNC, 2021]. The CNNC also aims to supply local governments with low-carbon hydrogen to facilitate emission reductions.

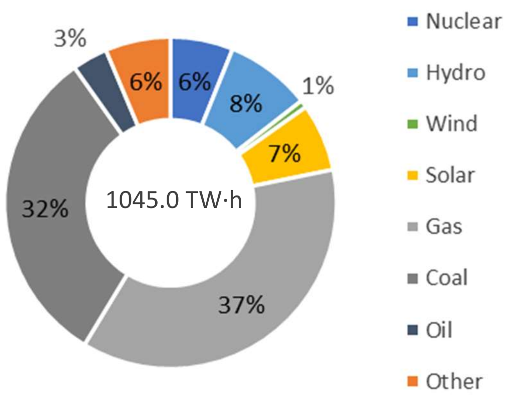
In 2021, China completed construction of a demonstration HTGR at the Shidao Bay NPP in northeast Shangdong province [World Nuclear News, 2021] and both units were connected to the grid in 2022. The development of high temperature reactors capable of highly efficient power generation and hydrogen production has been emphasized by the Chinese government and is receiving long-term support [Tsinghua University, 2010]. In addition to electricity, the high temperature steam produced by a high temperature reactor is being considered for multiple applications, including hydrogen production.

As can be seen in Figure 25, the share of renewable energy in China is still low, and so the CNNC has assumed that commercial hydrogen production from nuclear energy will be viable only after 2025 as the share of renewable energy increases and sufficient clean electricity is available. As of May 2024, the share of variable renewables has increased to 23% of China's electricity generation, a vast increase from 8% in 2019 (CarbonBrief, 2024). Hydrogen production from renewable energy in China is more flexible in terms of location and demand, and the price is expected to reduce in future, compared to hydrogen production from nuclear power [CNNC, 2021].

Japan

Japan has 31 679 MWe of operable nuclear power capacity (comprising 33 reactors) and was one of the first countries to develop a national hydrogen strategy. In 2021, the Japan Atomic Energy Agency (JAEA) restarted the High Temperature Engineering Test Reactor (HTTR), a 30 MW experimental HTGR in Oarai, Japan [JAEA, 2021b], and from 2022, the JAEA and Mitsubishi Heavy Industries were commissioned to start a demonstration project for hydrogen production by connecting the HTTR, which supplies high temperature heat via helium gas, to a hydrogen production plant [World Nuclear News, 2022]. In this project, licensing procedures, equipment modifications and tests will be carried out step by step to connect the HTTR to a hydrogen production facility using the SMR process. Following successful tests of the HTTR in 2024, JAEA is beginning screenings for connecting hydrogen equipment, with the aim to start producing hydrogen at the plant as soon as 2028 (Hydrogeninsight, 2024). In the interim, the agency is also developing low carbon hydrogen production technologies that include an S-I cycle, and these technologies will be used to demonstrate the capability of connecting the HTTR around 2040. Japan aims to use these technologies to provide a stable and economical supply of low carbon hydrogen in massive amounts by around 2050.

Figure 26. Japan generation in 2019



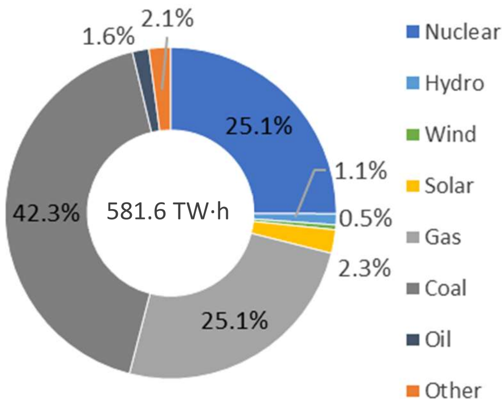
Source: based on data from Ref. IEA [2022].

On the other hand, no hydrogen production projects using existing NPPs currently exist in Japan. Although 12 NPPs have been restarted since the accident at the Fukushima Daiichi NPP, there are still 21 reactors which are under suspended operation, therefore the share of fossil fuel in Japan's electricity mix is still large (see Figure 26) (IAEA, 2024). There is not enough additional nuclear power in Japan today to produce hydrogen. In areas where high renewable energy capacity exists, supply may temporarily exceed demand. However, NPPs in Japan have a limited ability to adjust their output over a short time frame, given technical, regulatory and economic constraints, since Japanese priority feed-in rules have dictated that solar and wind output should be curtailed before nuclear power. As a result, when supply exceeds demand today, it may be possible to curtail renewable energy, but rarely nuclear power, meaning that there is almost no surplus nuclear power in Japan.

In addition, Japan imports its fossil fuels from expensive international markets, and both geographic and weather conditions are not conducive for large quantities of renewable energy. Since it is too costly for Japan to produce hydrogen from natural gas, coal or renewable energy, the country is focusing on importing hydrogen to secure a stable supply. In 2024 the Japanese parliament passed the Hydrogen Society Promotion Act which is targeted at providing subsidies for locally produced and low-carbon hydrogen. International hydrogen producers can therefore take advantage of both their own hydrogen subsidies and the Japanese subsidies if they export their hydrogen to Japan (Hydrogeninsight, 2024a).

Republic of Korea

Figure 27. Korea generation in 2019



Source: based on data from Ref. IEA [2022].

In the Republic of Korea, there are three projects underway to produce hydrogen from nuclear power. The first project is the Uljin Nuclear Hydrogen National Industrial Complex, which began building in 2022 near the Hanul NPP site in Uljin [The Korea Electric Times, 2022]. The national project will start to produce hydrogen using electricity and high temperature steam from existing nuclear power. Generation from nuclear power accounts for about a quarter of net electricity generation in Korea (see Figure 27). The project will commence with the demonstration of hydrogen production using a 5 MW LTE and the 50 kW HTE in phase 1, gradually transitioning to commercial hydrogen production with a 100 MW HTE by 2030 in phase 2. The combination of the HTE with an existing NPP is expected to demonstrate large-scale hydrogen production at a low cost. A critical aspect of cost reduction lies in addressing the heat requirements for HTE operation, which cannot be met solely by utilizing heat from existing NPPs. Therefore, the project encompasses a demonstration at an existing NPP in addition to the development of plans for designing and implementing HTGR technology to overcome this challenge. A memorandum of understanding for the project has already been signed between Uljin County, Seoul National University, Korea Electric Power Corp., the Korea Institute of Energy Research, the Korea Institute of Machinery and Materials, and Doosan

[Doosan, 2021]. In addition, Elcogen, a fuel cell and stacks manufacturer in Estonia, will cooperate to supply a large-scale HTE for the project. [Elcogen, 2022].

There are also plans for a Hydrogen Micro Hub in Seoul, which will produce hydrogen using SOEC technology using high temperature steam and electricity. From 2023 a 5-year joint R&D project has been agreed between Ultra Safe Nuclear Corporation (USNC), Hyundai Engineering and SK Plant to build a micro modular reactor (MMR) with an associated SOEC stack integrated into NPP for hydrogen production (Nuclear Engineering International, 2023). Each MMR is a HTGR with a thermal capacity of 15 MW and an electrical capacity of 5 MW. Unfortunately, USNC filed for Chapter 11 bankruptcy in October 2024 after the death of its principal investor which could end the process.

In June 2024 eight companies, including Hyundai Engineering, Doosan Energy, Korea Hydro and Nuclear Power, won $21 million of government funding to build a 10 MW pilot plant to produce hydrogen using LTE (Hydrogeninsight, 2024b). The low temperature means that SOEC technology cannot be selected for the project. By 2027 the project aims to produce four tonnes of hydrogen per day and the partners are to produce a business model for domestic and overseas export of hydrogen produced with nuclear energy. As of January 2025, there are no details as to where the plant will be built or which NPP will be providing power.

Additional countries considering nuclear hydrogen production

Other countries around the world are also considering hydrogen production from nuclear power, but their projects are in much more nascent development stages. The nuclear hydrogen project's status of other countries is detailed below in the order of the most concrete plans for near term nuclear hydrogen development to those that may inaugurate a nuclear hydrogen project in the more distant future — Brazil, Argentina, the UAE and France.

At the Angra NPP in **Brazil**, sodium hypochlorite is produced through electrolysis of sodium chloride and water. This process is employed for sterilization to prevent pipe corrosion caused by microbiota in the seawater used for cooling the tertiary loop of the NPP. Hydrogen is produced as a by-product of this process. Until now, this hydrogen has been released into the atmosphere, but a project has been launched to instead utilize the hydrogen. The current production volume of hydrogen is 150 kg/day, but the plan is to increase this amount to 300 kg/day, with further hopes to increase the amount to 500 kg/day in the future. The hydrogen will be used as fuel for fuel cells, power plants and hydrogen vehicles. Angra NPP is in the process of conducting a feasibility study (i.e. economic, technical and safety) to further capture and use the hydrogen for various applications, including self-consumption.

Argentina is in the process of exploring hydrogen production at existing NPPs. An evaluation of the cost of hydrogen with electricity from the CANDU reactor in Cordoba through the IAEA Hydrogen Economic Evaluation Programme (HEEP) has shown the cost to be $4/kg H_2 [IAEA, 2018a]. This estimate does not include the cost of storage and transport, and since there is little demand for hydrogen in industries nearby the NPP, the final cost would likely be higher. In addition, advanced reactors such as small modular reactors are considered to be a more realistic approach to hydrogen production in Argentina, because in the future, small modular reactors could be located nearby industries with a high demand for hydrogen, resulting in a major contribution to decarbonization. Progress in the construction of a CAREM small modular reactor near the Atucha NPP is currently at 85% completion [National Atomic Energy Commission of Argentina, 2024].

The **UAE** announced a Hydrogen Leadership Roadmap in 2021 with the goal of achieving a 25% share in the low carbon hydrogen market by 2030 [Emirates News Agency, 2021]. The country considers that hydrogen will not only play a key role in the UAE achieving Net Zero in 2050, but that it can also support world decarbonization through hydrogen export. The Emirates Nuclear Energy Corporation (ENEC) operates Barakah NPP which contains four reactors, the last of which came online in March 2024. Barakah NPP has 5321 MWe, with the potential to provide up to 25% of UAE's electricity generation (IAEA, 2024). ENEC has started efforts to explore hydrogen production with nuclear power and announced a cooperation plan with Électricité de France (EDF) for nuclear R&D in June 2021 [ENEC, 2021b].

France is positioned favourably to address the challenge of low carbon hydrogen. Over 90% of electricity generation is from nuclear and renewable sources, therefore electrolysers can be connected to the grid to produce low carbon hydrogen. In 2021 the French Government announced 'Plan France 2030' which is an investment plan to help the country meet its emissions targets [Government of France, 2021]. The plan includes a target to build two electrolyser giga factories by the end of the decade and to position France as a leader in low carbon hydrogen production by 2030. In an update to France's national hydrogen strategy in 2023, the country aims to install 6.5 GW of low carbon hydrogen by 2030, rising to 10 GW by 2030, with the government committing nearly $9.9 billion to support the development of decarbonised hydrogen (Hydrogeninsight, 2023). A total of $4.2 billion in investment aid and operating grants has been made available to support 1 GW of electrolysis capacity over the next three years. France considers that renewable energy capacity will never be enough for the electricity needed to produce sufficient low carbon hydrogen, and thus the country's NPPs could be a major asset [Dalton, 2021].

France also pushed for low carbon hydrogen to be included in the EU hydrogen strategy, such that hydrogen produced from nuclear power could also receive subsidies, alongside hydrogen produced from renewables.

In addition, in 2022, EDF announced a hydrogen plan that aims to develop 3 GW of electric hydrogen projects worldwide by 2030, which will involve between €2-3 billion of investment [EDF, 2022]. The group believes that the challenge lies in producing hydrogen as close to the demand site as possible to minimize hydrogen transport costs.

5. Demonstration project comparisons

Key points:

- A comparison of demonstration hydrogen production projects using electricity from existing nuclear power plants reveals several characteristics and challenges regarding motivations, the supply side, and the demand side.
- More specifically, many utilities use their own climate targets or their countries' hydrogen strategy as motivation for low carbon hydrogen production.
- On the supply side, cost reduction is recognized as the most important challenge, and each project is characterized in terms of the utilization of surplus energy and high temperature electrolysers, government financial support, and collaboration with other organizations.
- On the demand side, the most important challenge is to predict and secure near term and future hydrogen demand. The development of various target markets is being considered, along with the electrolyser location – including at nuclear power plants – and the promotion of projects involving end users.

Table 2. Roadmap for low carbon electricity

	2020s	2030s	2040s	2050s
Energy Harbor	• Become a 100% carbon free, energy and infrastructure supply company in 2023.	-	-	-
Xcel Energy		• Reduce carbon emissions from electricity by 80% by 2030.		• Provide 100% carbon free electricity by 2050.
APS		• Achieve 65% clean energy by 2030 with 45% renewable energy.		• Ensure 100% clean, carbon free electricity by 2050.
Constellation Energy		• Ensure 95% carbon free energy by 2030.	• Reach 100% carbon free electricity by 2040. • Ensure a 100% reduction in operations-driven emissions by 2040.	
EDF Energy	• Reduce the direct combustion emissions intensity of generation to zero by 2023.	• Reduce indirect emissions by 28%, compared to 2019, by 2030.		• Net zero by 2050
Vattenfall	• Reduce CO_2 emissions intensity by 43% by 2025.	• Reduce CO_2 emissions intensity by 77% by 2030.	• Achieve net zero emissions by 2040 for operations, both in the case of suppliers and customers.	
OKG (Uniper)	• Exit all coal-based activities by 2029.	• 55% reduction in CO_2 emissions by 2030 (direct and some indirect emissions).	• Carbon neutrality by 2040	
Bruce Power	• Achieve net zero GHG emissions (both direct and indirect) by 2027.			
Fortum	• Exit all coal-based energy production by 2027.	• Carbon neutrality by 2030, including direct and indirect emissions.		

Source: adapted from Ref. Energy Harbor (2022b); Xcel Energy (2022); APS (2020); Constellation Energy (2022a); EDF Energy (2021); Uniper (2024); Vattenfall (2021e); Bruce Power (2021); Fortum (2023). Rosatom does not have a stated goal for carbon neutrality, but is line with Russia's goal of net zero by 2060. Discontinued projects shown in red.

Utility strategy and climate targets

Numerous utilities leading nuclear hydrogen demonstration projects have set their own decarbonization targets, as illustrated in Table 2. Others have set climate targets to contribute to national decarbonization policies. Most utilities include hydrogen production with nuclear power as a part of their strategy to achieve the targets, and they are using these goals as motivation to move forward with nuclear hydrogen projects.

Also, the inclusion of nuclear hydrogen policies by governments are a major encouragement for utilities to pursue nuclear hydrogen projects. For example, Canada, the UK and the USA include hydrogen from existing nuclear power in their national hydrogen strategies and are positioning nuclear power as one of their leading methods of hydrogen production. Nuclear hydrogen energy in the Russian Federation has also gained state-level support, evidenced by a detailed action plan and concept officialized in decrees regarding hydrogen development.

Goals set spontaneously

To achieve a sustainable energy future, **Xcel Energy** has set ambitious goals to deliver 100% carbon free electricity by 2050, with an aggressive interim target to cut carbon emissions by 80% by 2030 (compared to 2005 levels) [Xcel Energy, 2022]. The utility has been adjusting its energy mix by integrating wind and solar power while phasing out coal power plants. With these economically viable technologies, the utility believes the interim target is achievable. Conversely, the utility has emphasized that beyond 2030, advanced carbon free, 24/7 power technologies at affordable prices will be needed to reduce the remaining 20% of carbon, therefore more innovation is required today. As one of these technologies, zero carbon fuels, wll be included in these ambitious goals.

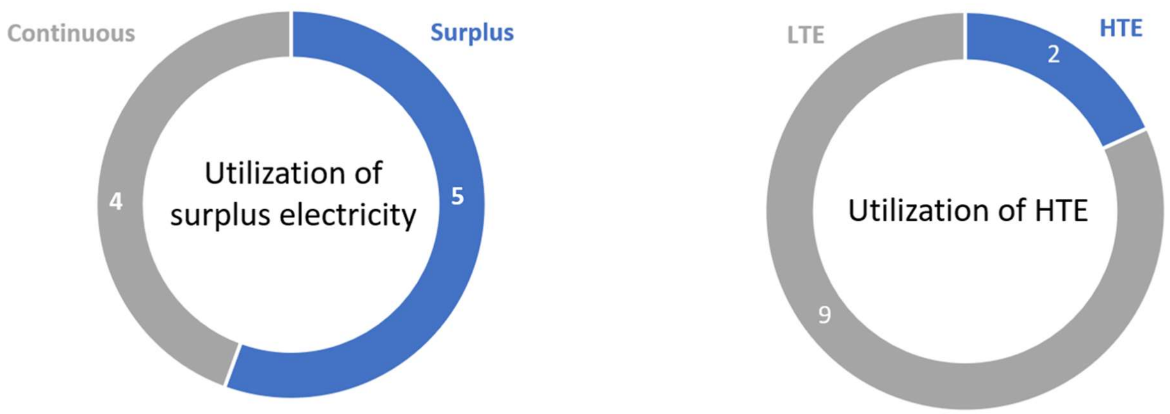
In 2020, APS announced its clean energy commitment to create a sustainable energy future for Arizona, outlining three goals: achieving “100% clean, carbon free electricity by 2050”, attaining “65% clean energy by 2030 with 45% renewable energy” and to “eliminate coal by the end of 2031” [APS, 2020]. This clean energy plan emphasizes that the goal is not just clean energy, but should also include affordable and reliable energy. The main pathways to achieve the goal are adding large-scale renewable energy, such as solar power and wind power, as well as battery storage facilities, although these will not be sufficient in the long term. The utility also considers that energy innovations, including hydrogen as another storage technology, are required, and that the continued pursuit of advancements in new and emerging technologies will be essential.

Constellation Energy has already reduced its emissions significantly and is committed to producing 100% carbon free electricity by 2040 [Constellation Energy, 2022a]. In the mass production of low carbon hydrogen, the utility considers that the combination of nuclear power and hydrogen can help to address the climate crisis, since some major obstacles exist in relation to cost and time when combining renewable energy and hydrogen in the USA [Constellation Energy, 2022b]. The company thus recognizes that it is uniquely positioned to solve this problem, because its NPPs are located close to heavy industry, and it has numerous customers seeking clean energy solutions.

Goals to help achieve national objectives

In 2020, **EDF Energy** made a commitment that includes four ways to help the UK achieve net zero emissions by 2050, one of which is ‘low carbon electricity’ [EDF

Figure 28. Number of utilities engaging in cost reduction methods



Source: based on data from Ref. IAEA [2021b]. Fortum are considering utilizing LTE, with no decision on utilization of electricity. EDF Energy are considering utilizing both LTE and HTE technology, so have been included twice when considering utilization of electrolysers.

Energy, 2021]. Low carbon electricity focuses on a way to accelerate the shift to low carbon nuclear and renewable energy. It also includes the exploration of hydrogen production using renewable energy and nuclear power. Hydrogen is expected to be used as a fuel for heavy goods vehicles, for example.

In 2020, **Bruce Power** announced 'NZ-2050', which is the company's strategy for helping Canada achieve its stated goal of net zero emissions by 2050 [Bruce Power, 2020b]. The strategy consists of five pillars, one of which involves producing hydrogen through nuclear power generation — "utilize nuclear power generation to produce clean fuels and electrify industrial processes and transportation." Building off this announcement in 2021, Bruce Power announced its commitment to achieve net zero GHG emissions from its site operations by 2027 [Bruce Power, 2021].

Minimizing costs to maximize revenue

Approaches to reducing costs

There are two main approaches to reducing the cost of low carbon hydrogen production for utilities. One is by reducing and optimizing the cost of inputs in relation to the hydrogen production process, and the other is to increase the efficiency of hydrogen production by using both electricity and heat.

Since the main cost of producing hydrogen using an electrolyser is the cost of electricity, using cheap surplus electricity from nuclear power could reduce the cost of hydrogen production. However, the cost of the electricity is higher for new NPPs, compared to LTO of an existing NPP. If NPPs can generate revenue by selling hydrogen, this new revenue stream is an opportunity to boost profits and maintain operational viability. Another approach to increase the efficiency of hydrogen production is to harness both the electricity and steam produced from existing NPPs by using advanced technologies. HTEs which utilize the nuclear steam by-product, are expected to increase the efficiency of hydrogen by about 10–30%.

As shown in Figure 28 on the previous page, five of the ten utilities surveyed are considering the utilization of surplus electricity (Fortum has not yet announced a decision), and two utilities are considering the utilization of the HTE, demonstrating that many utilities see great potential in the effective use of surplus electricity. It also shows that while many utilities are aware of the effectiveness of the HTE, they are aware that there are many challenges to adopting HTE in the place of LTE.

Utilization of surplus electricity

Xcel Energy considered constant operation of an electrolyser in its demonstration project since it would have only accounted for only a small percentage of the NPP's output. During the demonstration project, the intention was to operate the electrolyser using power from behind the meter at the NPP.

However, Xcel Energy has considered a different operating model for a large-scale system that would maximize NPP value. The NPP would be used to produce hydrogen continuously, except when electricity prices exceed high thresholds — Xcel Energy expects the total number of hours to be only three to six per day. This alternative operating model has the potential to maximize NPP revenue and reduce overall system costs.

PNW Hydrogen and APS planned to run their electrolyser during off peak demand periods to produce hydrogen when wholesale market conditions reflect low priced electricity from solar energy. The company expected to run the demonstration project electrolyser for 16 hours a day, since 8 hours a day electricity from the NPP would have been sold to meet the system load.

Constellation Energy considers that continuous operation of an electrolyser is the preferred option, and so during the demonstration project at Nine Mile Point the company has been operating the electrolyser in a continuous manner. However, since the electricity cost has a significant impact on the cost of hydrogen, consideration is being given to interrupting production if the electricity price is high. Preparations are therefore underway to develop a front-end controller in collaboration with partners. This device optimizes the operation of the electrolyser, turning the system on and off according to information input, such as electricity price forecasts, the status of hydrogen storage and hydrogen demand.

Rosatom announced plans to utilize excess electricity produced from NPPs for hydrogen production, and the Kola NPP was selected for the demonstration project because of its relatively low capacity factor [Rosatom, 2021b].

Bruce Power supplies Ontario's baseload generation from the Bruce NPP. Electricity customers in Ontario face a considerable difference in electricity prices during times of high demand compared to times of low demand because electricity rates in Ontario include an Hourly Ontario Energy Price, which changes through the day depending on electricity supply and demand [Independent Electricity System Operator, 2022]. For an electrolyser connected to the provincial grid, it would likely be economical to avoid production at times of highest electricity prices. Bruce Power will therefore attempt to produce hydrogen using optimized site electricity. In fact, Ontario sometimes has a surplus of baseload generation, and the Bruce NPP is applied in flexible plant operation [IAEA, 2018b]. At the same time, Bruce Power does not consider this method as the only possible economic model for hydrogen production; it is also exploring an economic model for continuous operations.

Improving efficiency through advanced technology

Xcel Energy planned to use steam and electricity from a NPP in HTSE through a demonstration project. The HTSE has the potential to be up to 30% more efficient than the LTE by boiling the water entering the HTSE with 150–200ºC steam from the Prairie Island NPP. The amount of steam required for the HTSE is much less than the amount of electricity required. If, for example, a 10 MWe HTSE was installed in future, 1.5 megawatt thermal (MWt) of steam would be required.

EDF Energy is also considering the use of heat and electricity from nuclear power generation to support electrolysis. The utility has concluded that steam at 180ºC will be sufficient for SOEC and will contribute to increasing the efficiency of hydrogen production by around >20% compared to PEM or alkaline electrolysis [Nuclear Industry Association, 2021], with minimal disruption to nuclear reactor technology. There are still significant challenges to deployment of SOEC technology, these are principally, the capacity of the electrolysers and rapid cell degradation. In 2023, Bloom Energy produced the world's largest SOEC with a 4 MW capacity, however most SOEC's are still on the kW scale and therefore not viable for large scale hydrogen production.

Appropriate capacity and production

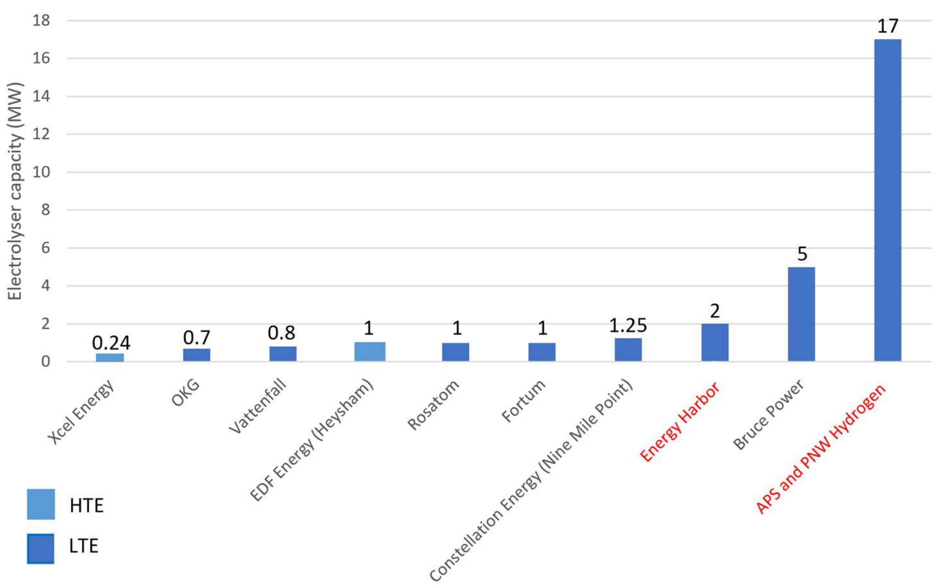
Electrolyser capacities are increasing because of the expected cost reduction from economies of scale. However, the capacity of the electrolyser in nuclear hydrogen projects remains small. As shown in Figure 29, almost all utilities using the LTE start with a small-scale demonstration project of around 1 MW, while those using the HTE start with an even smaller scale project. These demonstration projects tend to choose the electrolysis that is sized to meet the demand, which is small but highly reliable. However, after successful production on a small scale, the utilities also begin to consider gradually expanding the project to commercial scale.

Low temperature electrolysis

Energy Harbor aimed for a demonstration of a 2 MW LTE to produce commercial quantities of hydrogen.

PNW Hydrogen and APS considered the installation of a 17 MW PEM electrolyser in their demonstration project. This electrolyser was larger compared to other projects because it was intended to be used in the final phase (phase 3) of the consortium project with Energy Harbor and Xcel Energy. Specifically, the size of hydrogen production had been informed by the hydrogen blending estimated in the demonstration programme of hydrogen/natural gas co-firing at an APS-owned natural gas fired power plant. PNW Hydrogen and APS believed that the manufacturing of PEM electrolysers at scale would continue to drive the cost of electrolysers lower, while increasing the manufacturing capability and further enabling scale up.

Figure 29. The scale of electrolysers at the beginning of projects



Source: based on data from Ref. IAEA [2021b] and Ref. (2023)

Constellation Energy installed a 1.25 MW PEM electrolyser, manufactured by Nel Hydrogen, at the Nine Mile Point NPP. The company considers that the PEM technology is suitable for a small demonstration project, but potential scale-up technology is yet to be assessed. For the 2.3 GW La Salle project, Constellation Energy are yet to select the electrolyser technology.

Rosatom has actively developed LTE PEM units to replace alkaline electrolysers. Using this technology, a test facility with a 1 MW electrolyser has been built at the Kola NPP, but the electrolyser capacity will eventually be increased to 10 MW. Electrolysers and other main process equipment manufactured by Rosatom have been used in the creation of the bench-scale test.

Bruce Power's feasibility study on Bruce NPP concluded that hydrogen production from the facility was feasible, with a demonstration project beginning with a 5 MW electrolyser. A new feasibility study between Kinectrics and Fuel Cell Energy, supported by Bruce Power, is exploring hydrogen production from advanced SOEC technology.

High temperature electrolysis

Xcel Energy planned to produce 130 kg/day H_2 with a 240 kW HTSE in a pilot project. To meet the growing demand for hydrogen, Xcel Energy considered that it would have needed to increase the size of the HTSE in the future.

EDF Energy had plans to install approximately a 2 MW alkaline or PEM electrolyser to produce around 800 kg of hydrogen for various vehicles through a demonstration project powered by the Sizewell B NPP. However, in 2023 EDF Energy and partners received a government grant to build a 1MW demonstration project which will use SOEC technology at Heysham as part of the Bay Hydrogen Hub.

Government support

Many of the projects described in this report have either benefitted from government support for a FOAK demonstration, or the project has been scrapped if government support is no longer available. When the USA announced seven hydrogen hubs as part the 2023 hydrogen strategy, projects which had been proposed and were selected as part of a hydrogen hub continued, such as Nine Mile Point, whereas projects which did not receive support were deemed economically infeasible. Future projects in the United States, such as LaSalle, are dependent on financial government support, which includes tax credits of up to $3/kg for clean hydrogen. Initially the future of hydrogen production from existing nuclear appeared bleak under the original 45V tax credit, however in 2024 existing nuclear facilities were deemed eligible for tax credits.

A similar challenge has faced projects in the UK, where the status of the Sizewell B project is unclear, whereas the Heysham project received UK government funding in 2023 with aim of a demonstration plant by 2025. In Sweden, the HYBRIT project received a total of €143 million from the EU innovation fund in 2022 and an additional equivalent of $300 million in 2023 from the Swedish Energy Agency, however HYBRIT is a larger project which includes hydrogen production and use of hydrogen to decarbonise steel. The Oskarshamn plant in Sweden was already producing hydrogen and only needed to find an off taker for additional hydrogen production after units 1 and 2 were closed in 2017 and 2016 respectively, therefore there was no government involvement in the project.

In Canada, the government of Ontario have started a Hydrogen Innovation Fund, of which a feasibility study by Kinectrics and FuelCell Energy, supported by Bruce Power, have received a share of the $5.5 million fund. The feasibility study is focused on integrating hydrogen production, hydrogen power generation and setting up a hydrogen fuelling station at a hydrogen hub in

Table 3. Collaboration with laboratories, companies and end users

	Laboratories & Universities	Electrolyser companies	End users
Energy Harbor	✓	✓	✓
Xcel Energy	✓		
APS and PNW Hydrogen	✓	✓	
Constellation Energy	✓	✓	
EDF Energy	✓		✓
Rosatom			
Vattenfall			✓
OKG			✓
Bruce Power		✓	✓
Fortum			

Source: based on data from Ref. IAEA [2021b]. No partners have been announced for the Rosatom or Fortum projects as of August 2024

Toronto. However, the Bruce NPP project has not received regional or national public investment and the project has not transitioned from the feasibility study which was concluded in 2022.

In 2024, the Republic of Korea's Ministry of Energy, Trade and Industry granted $21 million to eight companies, to build a 10 MW hydrogen production plant at an existing nuclear plant by 2027. However, it is too early to say whether further government funding will be required for this project to be realised.

How to proceed with nuclear hydrogen projects

Thus far, two primary means have been adopted to better allocate nuclear hydrogen projects and minimize losses: (a) collaboration with other organizations; and (b) the milestone approach.

Collaborating with other organizations makes a project more complex and difficult to control; however, it can complement technical capabilities and spread the cost and losses of the project more broadly. As shown in Table 3, nuclear hydrogen demonstration projects can be broadly categorized into cases in which utilities collaborate with laboratories and universities, electrolyser companies or end users. Utilities that want to enhance the technical aspects of hydrogen production collaborate with laboratories or electrolyser companies. On the other hand, utilities that want to secure or develop a reliable hydrogen demand cooperate with end users.

Some projects also attempt to minimize losses in the case of failure by setting milestones before starting the project so that they can decide whether to proceed at each step of the project.

Collaboration with companies and laboratories

Energy Harbor, **Xcel Energy**, **PNW Hydrogen, APS** and **Constellation Energy** have previously or are working in a consortium with the INL to receive technical support for hydrogen production. **Energy Harbor** and others launched the GLCH coalition with the goal of creating a hydrogen supply chain and job opportunities by using a NPP as a major hub for hydrogen production. The coalition included, as major end users, Cleveland-Cliffs, which intended to use hydrogen for steelmaking; the Toledo Area Regional Transit Authority, which proposed a project to operate hydrogen buses; and GE Aviation, which considered the use of hydrogen as an alternative jet fuel. In addition, four national laboratories and five universities will undertake research on the technical challenges of using hydrogen and will support the commercial deployment of hydrogen [The University of Toledo, 2022]. However, GLCH was not one of the seven hydrogen hubs selected by the US government to receive a share of $7 billion and was scrapped in 2023.

Xcel Energy collaborated with the ANL, NREL and EPRI, in addition to the INL, to complete a technoeconomic analysis of regional nuclear-to-hydrogen integration opportunities at both Prairie Island and Monticello NPPs. The analysis was funded by a 2019 award from the DOE to support development of clean hydrogen and was completed in 2022 (NREL, 2022). Multiple stakeholders were also engaged in research, academia, industry and state level government with the **PNW Hydrogen and APS** project. Among these partners was OxEon Energy, which is developing SOECs, and was selected to provide insight on the electrolyser.

Constellation Energy collaborated with Nel Hydrogen, the INL, the ANL and the NREL to successfully begin hydrogen production at Nine Mile Point NPP. The NREL and Nel Hydrogen developed the PEM electrolyser, and the INL developed a front-end controller to ensure dynamic operation. The ANL is surveying hydrogen demand and infrastructure in the area surrounding the NPPs for potential scale-up sites.

EDF Energy collaborated with Lancaster University, the European Institute for Energy Research and Atkins consulting firm, to conduct the 2019 feasibility study for hydrogen production at the Heysham NPP. The second feasibility study, the Hydrogen Bay Hub initiative, which includes Heysham NPP, is being conducted in association with the National Nuclear Laboratory (NNL) and Vulcan Burners. Sizewell B and C NPPs will be a part of an energy hub for Freeport East and will supply hydrogen to meet the local requirements for maritime activities, such as those involving port equipment, marine vessels and transport, including hydrogen buses, trucks, trains, construction and agriculture vehicles. In 2021, Ryze Hydrogen planned to collaborate on the Sizewell B project and help to install a 6 MW electrolyser at the site (Bamford, 2021). Also participating in the scheme are Wrightbus, a bus manufacturer, and JCB, who manufacture equipment for construction, agriculture, waste handling and demolition.

Vattenfall is part of HYBRIT, a collaboration between the LKAB mining company and SSAB steel producer, supported by the Swedish Energy Agency. The project is also supported six Swedish universities and research institutes and engineering group Sandvik.

Bruce Power conducted a feasibility study which explored the possibility of using excess energy for hydrogen production. The study was led by Arcadis and supported by the Nuclear Innovation Institute and project partners Greenfield Global (Nuclear Innovation Institute, 2021). In 2023 a different feasibility study was completed with partners Greenfield Global, Hydrogen Optimized, BPNZ, Hatch and Hensall Co-op in partnership with the Hydrogen Business Council, to determine if a hydrogen hub could be developed in the region (Nuclear Engineering International, 2022). The study identified that as demand for hydrogen grows, a hydrogen hub is feasible between Bruce, Grey and Huron counties. A third feasibility study began in 2023, in collaboration between, Kinectrics and FuelCell Energy, to determine whether there is potential for a hydrogen hub in Toronto which would use SOEC technology for hydrogen production.

Milestone approach

Constellation Energy divided its nuclear hydrogen demonstration project into budget periods 1 and 2 for Nine Mile Point NPP. Budget period 1 included site selection and initial engineering design. In August 2021, the decision was made to proceed to budget period 2. In 2022, the DOE approved construction and installation of an electrolyser system at the NPP with an award of $5.8 million. In budget period 2, the developed electrolyser was installed, and hydrogen production began in 2023. The company then proposed the LaSalle project as part of the MachH2 hydrogen hub after the success of Nine Mile Point.

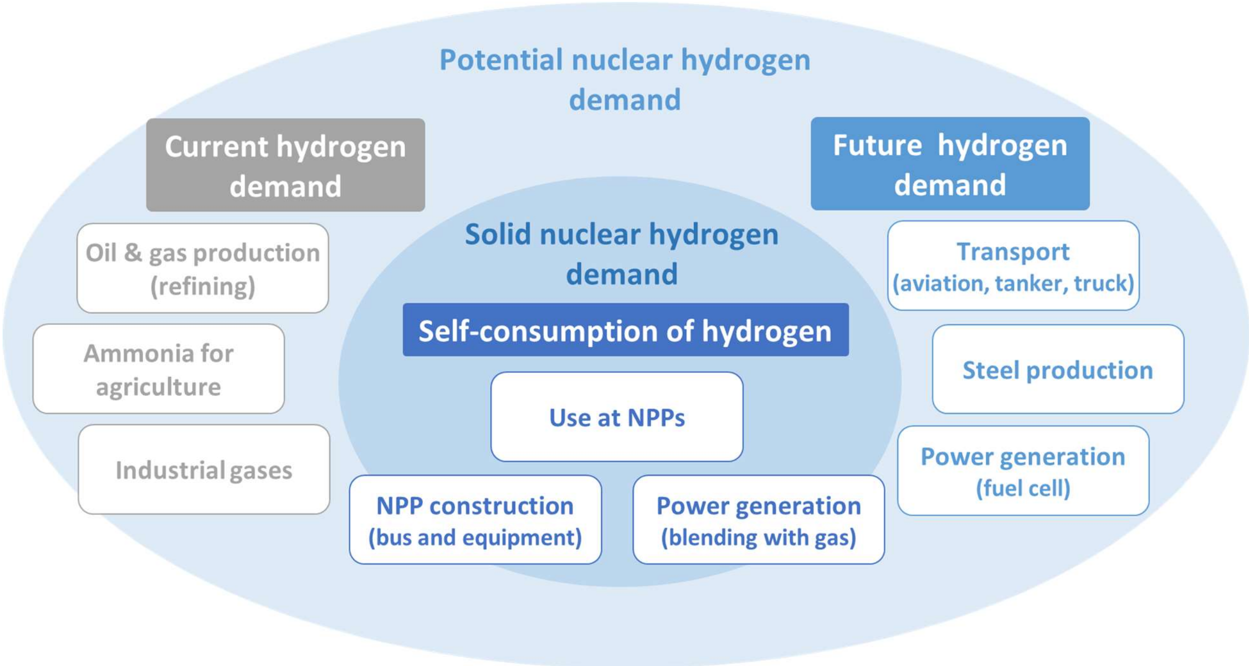
EDF Energy's Hydrogen to Heysham project was divided into a feasibility study during phase 1, completed in 2019, and demonstration in phase 2. During phase 1, it was confirmed that the system was technically feasible, with compliance in relation to all the relevant safety requirements. There was strong interest from local customers, but the hydrogen price was not competitive at the time of evaluation. Given these commercial challenges, the original project did not proceed to phase 2. However, in 2022 the UK Government announced new support for nuclear hydrogen production, with an initial £400,000 received by an EDF-led consortium, and in 2023 the Bay Hydrogen Hub received an additional £6.1 million from the UK Government. The new funding is for a phase 1 feasibility study to address the use nuclear hydrogen production using SOEC technology to decarbonise asphalt production.

Demand and market

Finding or creating demand for hydrogen

Another challenge for nuclear hydrogen demonstration projects is finding enough demand to incentivize hydrogen production in the first place. This 'chicken and egg' problem has meant that utilities often need to get creative with offtake solutions. Many nuclear hydrogen projects are still in the demonstration stage, and the amount of hydrogen produced is small. As shown in Figure 30, utilities are implementing or planning to use hydrogen produced at NPPs for their own use, such as to cool generators or add it to the primary cooling water. This helps to suppress the generation of oxygen due to radiolysis, and to prevent corrosion cracking of

Figure 30. Nuclear hydrogen demand development



Source: based on data from Ref. IAEA [2021b].

materials by reducing the presence of dissolved oxygen. If the owners of the nuclear hydrogen projects also own natural gas fired power plants, they may consider blending hydrogen with natural gas and using it as fuel, lowering the emissions of the gas plant and producing a reliable demand for hydrogen production. On the other hand, when the nuclear hydrogen project is scaled up, utilities can then consider replacing hydrogen demand from oil refining and agricultural ammonia production (i.e. hydrogen produced using fossil fuels) with low carbon hydrogen. These utilities can also expect to capture the demand from transport, steel production and fuel cell generation in the future.

Energy Harbor and partners proposed the GLCH Hub which aimed to help major industries, located near Davis-Besse NPP in the Midwest, to decarbonise. The project also focused on the growing market for transport, such as trucks, buses and aviation.

Xcel Energy evaluated that due to the small scale of hydrogen production planned at Prairie Island, the hydrogen would only be used at Prairie Island NPP. The company also owns the Monticello NPP 145 km from Prairie Island and consideration was underway to determine whether it would have been economical to store and transport hydrogen from Prairie Island to Monticello NPP. The Heartland Hub proposal has been designed to decarbonise multiple sectors, including agriculture and industrial manufacturing by producing clean hydrogen for fertiliser and power generation.

PNW Hydrogen and APS planned to blend 30% hydrogen with 70% natural gas, and to co-fire it as a fuel at an APS- owned peaking natural gas fired power plant (the APS Saguaro gas fired power plant, unit 3, with 71 MWe) in this project. They also had a more ambitious goal of co-firing up to 50% hydrogen without any mechanical changes to the plant, although there could have been some complications related to air quality permits. PNW Hydrogen and APS avoided regulatory issues with this demonstration project by selecting a site that was small enough to avoid having to obtain an environmental compatibility certificate.

Constellation Energy is using hydrogen produced at Nine Mile Point NPP with hydrogen to offset O&M costs in the demonstration project. In the future, Constellation Energy is considering the use of stored hydrogen to generate electricity during peak hours, the injection of hydrogen into gas pipelines or its transport for sale to hydrogen markets. The company focused on hydrogen demand as one of the determining factors for the demonstration project site and conducted a study of potential hydrogen demand in the future within 40 km of Constellation Energy's NPPs. For example, Constellation Energy estimated the hydrogen demand emanating from natural gas power plants, ethanol production facilities, and iron and petroleum refineries in the area around the Dresden Generating Station in Illinois, USA.

EDF Energy plan to use hydrogen produced from the Sizewell B NPP for buses and construction equipment for the Sizewell C NPP. In the future, the hydrogen produced from the Sizewell B and C nuclear power stations could supply local manufacturers and ports within the planned Freeport area.

Rosatom plans to use hydrogen produced at the Kola NPP for local partners around the NPP, such as industry, transport and energy sectors, as well as for export. Depending on future demand, the NPP could produce ammonia, methanol or other synthetic fuels.

In cooperation with potential industrial consumers, Rosatom is working on various possibilities for the use of low carbon hydrogen in the Russian Federation. It is in the beginning phases of commercializing hydrogen supply in local markets, including through mobility projects using fuel cells and industrial facilities. To develop these hydrogen markets, the company is working on R&D related to consumption, such as developing hydrogen fuel cells and providing solutions to industry and transport for decarbonization. The company previously considered hydrogen production for export across Europe and the Asia-Pacific, however since 2022 this export potential is no longer possible.

Vattenfall has been producing hydrogen at the Ringhals NPP and supplying it to the plant. The utility has now applied this experience to the production of hydrogen from a renewable energy source and has expanded the scope of hydrogen demand to include biofuel and steel production.

OKG plans to use hydrogen at its own NPP and to distribute any excess hydrogen to gas companies. A gas sales agreement has already been established with Linde Gas in 2022 and in 2024 a new contract was signed with Hynion to supply to hydrogen fuelling stations.

Bruce Power has listed promising local markets for hydrogen, including fertilizer production, power and heat for heavy industry, blending with natural gas, transport trucks and commuter trains.

Electrolyser system location

Where to locate the electrolyser system can be a challenging decision to make — as shown in Figure 31, whether it is located at the nuclear power site or closer to end use applications depends on many factors, each specific to the individual project.

When hydrogen is produced close to the energy source, there are no grid costs and the ability to use existing hydrogen storage facilities at NPPs. For hydrogen to be used outside of the NPP, however, transport — either by gas pipeline, trucks or ships— would be necessary.

The low energy density of hydrogen makes it difficult to transport, and this will have a significant impact on the total cost of hydrogen. In addition, for a small demonstration project, a licence amendment review is not expected to be required, but for larger production, a comprehensive regulatory review may be needed.

On the other hand, in the case that hydrogen demand is certain, for example for fuel at a natural gas power plant, the electrolyser is planned to be sited around the end use facilities.

Close to the energy source

Energy Harbor, **Constellation Energy**, **EDF Energy**, **Rosatom** and **OKG** either planned or are planning to locate LTEs near NPPs, and there are several reasons for this. Energy Harbor, for instance, aimed to reduce both the electricity and transmission costs associated with the electrolyser by situating it close to the Davis-Besse power plant, thereby establishing competitive pricing. Constellation Energy and EDF Energy are prioritizing the use of hydrogen at their own NPPs, and Energy Harbor also expected to become a customer of its own hydrogen production. Rosatom is working on the development of systems for compressing or liquefying hydrogen, alongside transportation methods, as part of an on-site demonstration project for hydrogen production. OKG originally used the onsite hydrogen production at Oskarshamn NPP for internal use, hence its proximity to the plant, however since units 1 and 2 have closed the surplus hydrogen production has been targeted at external demand beyond the NPP.

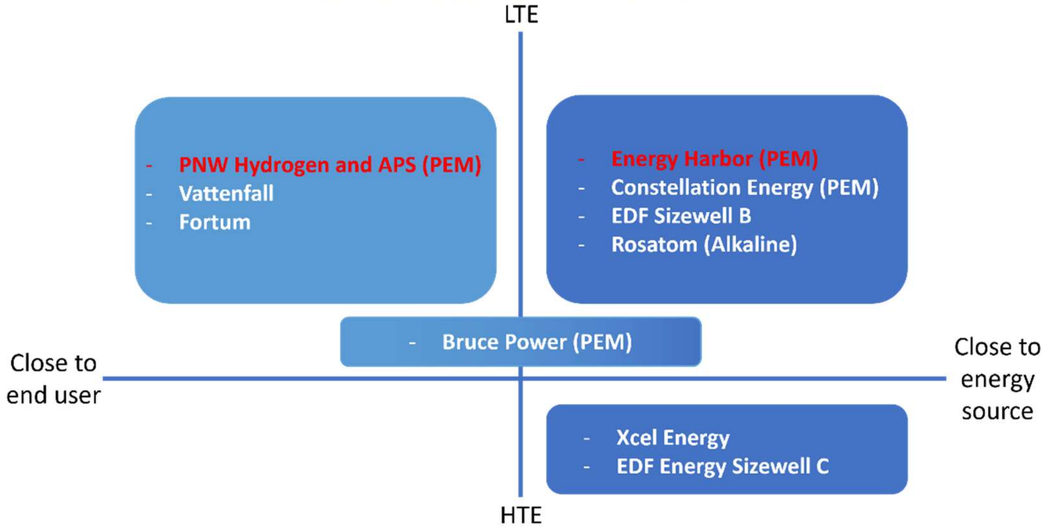
Xcel Energy and **EDF Energy** have considered the installation of HTEs next to NPPs to minimize the distance needed to transport the steam. Xcel Energy needed to navigate the regulatory procedures for its small-scale demonstration project while assessing the plant modifications required for HTE. These modifications are more complex compared to those for the LTE, due to the integration of the plant's high temperature steam. This integration demands additional piping and heat transfer infrastructure modifications, in addition to enhanced radiation shielding, which are all dependent on reactor type (Clean Air Task Force, 2023). Xcel Energy is also working with INL to form a regulatory peer group that will involve the NRC investigating regulatory concerns for future large-scale projects.

Close to end users

PNW Hydrogen and APS planned to locate their hydrogen electrolyser at the APS Saguaro gas fired power plant, unit 3, which is about 170 km away from the Palo Verde NPP. Locating the electrolyser at the end use facility avoids the need to transport the hydrogen. PNW Hydrogen and APS would have used a special contract to purchase nuclear electricity from the Palo Verde NPP for the period of its demonstration project.

Vattenfall has installed its demonstration electrolysers at a steel plant and a chemical plant, both of which have substantially high electricity demands and utilize electricity from the grid to produce hydrogen. Additionally, a large hydrogen storage facility has been built and was opened in 2022 next to the steel plant. To reduce the cost of hydrogen, production will only occur when the electricity price is low, and the hydrogen can then be stored until it is required for use. The hydrogen storage has been tested commercially on the electricity market and did show a reduction in hydrogen production cost of between 25 to 40%. In the future, avoiding significant grid connection costs will be a challenge.

Figure 31. The type and location of the electrolyser



Source: based on data from individual projects. Not included are the LaSalle project and the Toronto Hydrogen hub, where details of the electrolyser are unannounced.

Multiple locations

For its demonstration project, **Bruce Power** is considering multiple locations, for example placing the electrolyser nearby the Bruce NPP would allow for synergies between electricity supply and generation of hydrogen. However, for the Toronto hydrogen hub, off-site and closer to the end user may reduce transportation costs and infrastructure of hydrogen. However, hydrogen that is produced can only be considered low carbon if it can be demonstrated that it was produced using electricity from the NPP or a low carbon alternative.

Creating demand through clusters

To address the challenge of ensuring a consistent demand for hydrogen, various initiatives are underway to create hydrogen clusters. Several hydrogen cluster projects, incorporating hydrogen production from existing NPPs, have commenced. Concentrating the demand for hydrogen in these clusters would facilitate intensive infrastructure development.

EDF Energy is participating in the Freeport East Hydrogen Hub initiative and plans to generate a large amount of hydrogen via nuclear energy, initially at the Sizewell B NPP, and then at the Sizewell C NPP once it is commissioned. A cluster-based approach to hydrogen supply and demand will allow for a quick rollout of hydrogen buses, trucks, trains, and construction and agriculture vehicles across the London region and beyond. It is also expected that hydrogen applications will be rapidly developed to power equipment and marine vessels at the Felixstowe and Harwich ports. EDF Energy is proposing solutions through electrification and hydrogen use to increase the use of electricity and hydrogen from nuclear power in industrial processes, and transportation sectors. Due to the characteristics of the port cluster, nuclear power has been selected as the primary technology for hydrogen supply and will be supplemented by offshore wind. At peak capacity, the aim is to produce 1 GW of hydrogen. Freeports are areas designated by the UK Government which benefit from special customs and tax benefits with the aim to boost investment and trade.

Rosatom's Kola NPP is part of the West hydrogen cluster currently under development. This cluster is expected to pair a potentially large demand for hydrogen with the hydrogen supply from nuclear power. To minimize the transportation distance for hydrogen exports, hydrogen clusters in the Russian Federation tend to be established in close proximity to their intended export markets. Since 2022 the Russian export market has become limited, and it is uncertain as to whether this cluster will be developed due to the reduced demand from exports.

Constellation Energy and partners proposed the MachH2, one of seven hydrogen hubs selected by the DOE to receive a share of $7 billion to develop clean hydrogen. MachH2 hub will combine hydrogen production from nuclear and renewable technologies and support development of novel electrolysers, for use in heavy transportation, manufacturing and combined heat and power. Each of the seven hubs across the United States will use a variety of different methods to produce hydrogen, with the potential of nuclear to produce hydrogen in three of the selected hubs. The specific uses of hydrogen will also depend on the nature of the region in which the facilities are built, for example the hydrogen hub in California will have applications including port operations and the Heartland hub will help to decarbonise ammonia production.

6. Conclusions

Factors for deployment at present

For hydrogen produced from nuclear power to be implemented on a larger scale, it is important to leverage demonstration projects and use their results to inform future initiatives. Similarities, differences, and challenges can be examined to determine whether certain project attributes are transferable to other projects or if they are tailored to the unique goals of the demonstration projects in question. In the case of hydrogen demonstration projects, some similarities and differences have been observed, as shown in Figure 32.

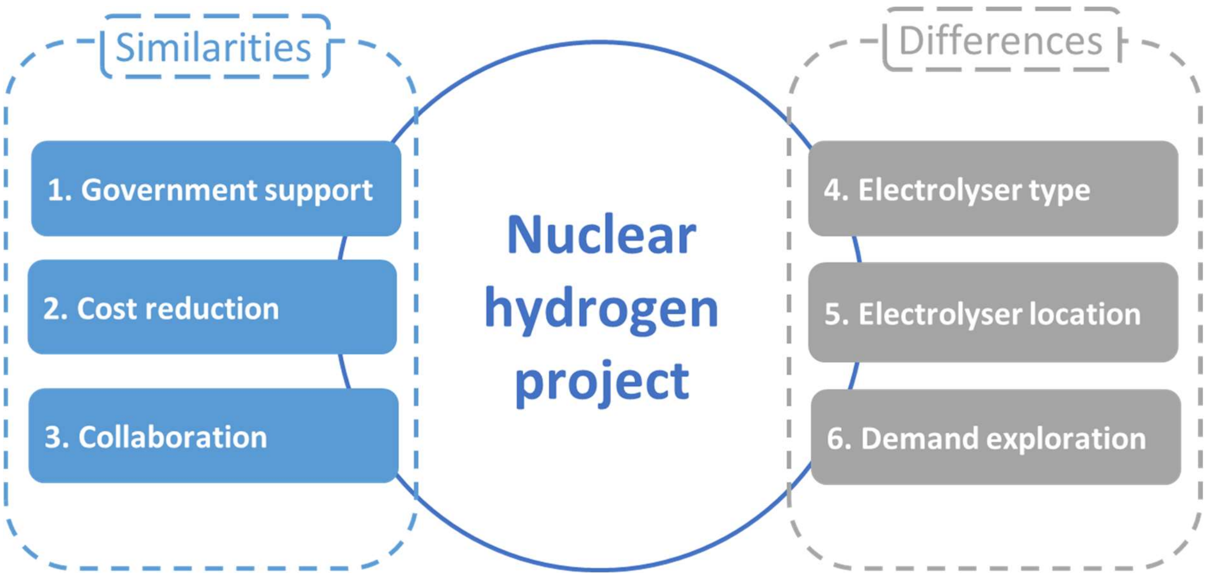
Some of the observed similarities between projects include:

- Government support in various forms has been critical in promoting projects. Hydrogen projects based on existing nuclear power plants still lack economic competitiveness compared to fossil fuel-based hydrogen production. It remains uncertain as to whether these projects will be profitable and sustainable in the future, making it challenging for utilities to invest significant amounts in them. Although these projects may entail higher risks, utilities that are able to receive government funding are actively pursuing such projects to reduce their own project costs. In addition, incorporating hydrogen production using existing nuclear power plants in national hydrogen strategies or roadmaps provides additional reassurance for utilities by increasing certainty in the future viability of such projects.
- Pathways to obtaining cheap electricity for hydrogen production vary. To mitigate the cost of electricity, which constitutes the majority of hydrogen production cost, it is advantageous to produce hydrogen when electricity costs are low. For example, hydrogen production could be scheduled during periods of surplus electricity generated by renewable sources or nuclear power, as well as during off-peak hours when demand is minimal, such as during the night. These approaches would prevent the need to either curtail nuclear power or sell electricity at reduced prices.
- Several approaches are being employed to increase the probability of success and minimize the cost and losses. Up to now, demonstration projects have remained small to keep costs relatively low. For many projects, the size of the electrolyser has been 1 MW or less. Most have started with a small amount of hydrogen production with plans to gradually scale up. To ensure a viable use case, these projects have been conducted in collaboration with research institutes, electrolyser manufacturers, and companies requiring hydrogen, rather than being pursued independently.

Some differences that were observed in demonstration projects include:

- The electrolyser selected for each project is different, with no clearly defined superior technology to date. Low temperature electrolyser (LTE) technologies, such as alkaline and proton exchange membrane (PEM) electrolysers, have been

Figure 32. Factors related to current hydrogen project deployment



Source: based on data from Ref. IAEA [2021b].

used on a commercial scale, but each has advantages and drawbacks, including capital expenditures, limitations on rapid output adjustments, efficiency, size and durability. While many projects opted for LTE technology, some projects chose the high temperature electrolyser (HTE) technology to take advantage of the characteristics of nuclear power, which generates both electricity and heat. The HTE technology is expected to show some increases in efficiency compared to the LTE technology because it also uses heat. However, the HTE has some technical issues to be resolved, including rapid cell degradation. It is for this reason that few large-scale HTE projects exist today. In addition, there are also regulatory issues, for example additional radiational shielding, which concern installations that are next to a nuclear power plant (NPP).

- The location of the electrolyser can be situated either near the NPP or near the hydrogen demand facility, allowing it to utilize nuclear electricity via the grid in the latter scenario. On-site hydrogen production is optimal when the hydrogen is primarily utilized by the NPP. Conversely, when hydrogen is produced on-site for use elsewhere, the challenge of transporting the hydrogen to the end use location becomes a significant factor. Choosing to locate the electrolyser near the hydrogen demand facility is beneficial when the hydrogen is mainly used by a large demand facility, such as a thermal gas power plant or a steel production plant. Opting to locate the electrolyser closer to the demand facility nevertheless presents its own challenges, such as grid interconnection and the associated costs, as well as certification issues related to hydrogen production using electricity from NPPs. Both cases show the significance of not only considering the cost of hydrogen production but also evaluating the total cost, including transport and storage.
- Each project reflects regional and market characteristics. Some projects target hydrogen demand facilities in neighbouring areas, while others aim to export hydrogen. Hydrogen clusters are one approach to boosting both the demand and supply of hydrogen simultaneously. While each project may target a different market and employ different methods of finding or creating markets, it is crucial that all utilities share the search for a reliable revenue stream for their hydrogen project.

Some of the challenges that have been observed in demonstration projects include:

- Regulatory barriers caused by modification of an existing plant. Depending on the type of reactor, additional protection measures may be needed against potential explosion risks (blast effect), and this could require the national regulator to re-evaluate the site licence. The potential benefits of HTE are the ability to use both high temperature steam and electricity from the NPP to increase efficiency of hydrogen production, however this benefit will need to be considered against the additional regulatory challenges compared to LTE.
- Financing projects without governmental support. All of the projects which have begun producing hydrogen or are still under development have required substantial government support in the form of grants to assist with feasibility studies and construction. In addition, if hydrogen produced from nuclear is to be cost competitive with other forms of low carbon hydrogen, incentives such as low carbon tax credits, must apply to hydrogen production from nuclear power. The cost of low carbon hydrogen is not yet cost competitive with hydrogen produced from fossil fuels, so without subsidies or carbon taxes applied to hydrogen produced from fossil fuels, low carbon hydrogen cannot be cost competitive.
- A taxonomy which has emerged that uses a colour scheme to indicate the source or process of hydrogen production [Bulletin H2, 2021]. While this taxonomy may serve as a useful reference for some users, it places too much emphasis on factors other than the carbon intensity of the hydrogen, potentially excluding low carbon technologies crucial for hydrogen production. For hydrogen to achieve widespread acceptance and deeply penetrate global decarbonization efforts, objective, transparent, verifiable, and harmonized methods are expected to be established to measure hydrogen's carbon intensity.
- Hydrogen can fulfil roles in both electric applications, such as serving as an energy storage tool, and non-electric applications, including transportation or industrial processes. When a deregulated power asset produces hydrogen that is used for both electric and non-electric applications, the cost of the electrolyser will either be included in the hydrogen or electricity price, depending on the application. As the hydrogen market matures, hydrogen producers transition between producing electricity and hydrogen, deregulated power assets are likely to include the opportunity cost of hydrogen in their electricity offers to optimize operational efficiency.

However, due to regulatory constraints, hydrogen generated by regulated power assets may require allocation of electrolyser costs to their customers. Consequently, these assets are likely to be limited to selling hydrogen exclusively for electric applications. In regulated power markets, the electricity price paid by customers is the sum of capital investments and other costs incurred by the regulated utility. For this reason, utilities operating in regulated electricity markets may have to consider facilitating deregulation to leverage hydrogen for non-electric applications.

Future development and scheduling of the demonstration projects

Nearly all nuclear hydrogen projects are currently in the early stages of demonstration, with most hydrogen production yet to commence. These projects are anticipated to be completed over the course of several years. As the cost of hydrogen from existing nuclear is not yet cost competitive compared to that produced from fossil fuels, projects require government support or/and strong carbon market policy to be economically relevant. There is already evidence that projects which do not have government support, such as Davis-Besse or Palo Verde, have been scrapped. It is beneficial to monitor existing projects closely in order to identify other successes and challenges in the deployment of hydrogen production using electricity from NPPs. As nuclear hydrogen projects transition to commercial scale, it is important to identify how to resolve emerging challenges, such as scaling up the electrolyser, compliance with regulatory requirements, transporting and storing hydrogen, fostering additional demand for hydrogen, ensuring water sustainability, and engaging with stakeholders and the public.

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List of abbreviations

AEM	anion exchange membrane
AGR	advanced gas cooled reactor
ANL	Argonne National Laboratory (USA)
APS	Arizona Public Service Company
BPNZ	British Petroleum New Zealand
BWR	boiling water reactor
CAPEX	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, utilization and storage
CO	carbon monoxide
CO_2	carbon dioxide
CNNC	China National Nuclear Corporation
Cu-Cl	copper-chlorine
DOE	Department of Energy (USA)
EDF	Électricité de France
EIA	Energy Information Administration (USA)
EIFER	European Institute for Energy Research
ENEC	Emirates Nuclear Energy Corporation
EPR	European pressurized water reactor
EPRI	Electric Power Research Institute (USA)
ETC	Energy Transitions Commission
FOAK	first of a kind
FORATOM	European Atomic Forum (now ‘nucleareurope’)
g CO_2 eg/kW·h	grams CO_2 equivalent per kilowatt hour
GHG	greenhouse gas
GLCH	Great Lakes Clean Hydrogen
GW	gigawatt
GW·h	gigawatt hour(s)
H_2	hydrogen
HEEP	Hydrogen Economic Evaluation Programme (IAEA)
HTE	high temperature electrolyser
HTGR	high temperature gas cooled reactor
HTSE	high temperature steam electrolysis
HTTR	High Temperature Engineering Test Reactor
HYBRIT	Hydrogen Breakthrough Ironmaking Technology (Sweden)
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INL	Idaho National Laboratory (USA)
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
JAEA	Japan Atomic Energy Agency
kg	kilogram
kW	kilowatt
kW·h	kilowatt hour(s)
LCOE	levelized cost of electricity
LCOH	levelized cost of hydrogen
LHV	lower heating value
LKAB	Luossavaara-Kiirunavaara AB (Sweden)
LTE	low temperature electrolyser
LTO	long term operation
MachH2	Midwest Alliance for Clean Hydrogen
MMR	micro modular reactor
MW	megawatt
MWe	megawatt electric
MWt	megawatt thermal
MW·h	megawatt hour(s)
NE	Office of Nuclear Energy (USA)
NIA	Nuclear Industry Association
NNL	National Nuclear Laboratory (UK)
NPP	nuclear power plant
NREL	National Renewable Energy Laboratory (USA)
NYSERDA	New York State Energy Research and Development Authority
O_2	oxygen
O&M	operations and maintenance
OKG	OKG Aktiebolag
OPEX	operational expenditure
PEM	proton exchange membrane
PHWR	pressurized heavy water reactor
PNW	Pinnacle West Capital Corporation
PWR	pressurized water reactor
R&D	research and development
S-I	sulphur-iodine
SMR	steam methane reforming
SOEC	solid oxide electrolyser cell
SSAB	Svenskt Stål AB
TW·h	terawatt hour(s)
USNC	Ultra Safe Nuclear Corporation
VVER	vodo voddyanoi enyergeticheskiy reaktor (water-water energetic reactor)

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