Hydrogen Production with Operating Nuclear Power Plants

Business Case

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Contents

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 the option of hydrogen production using electricity from operating nuclear power plants.
- More and more countries are developing comprehensive hydrogen strategies, with some having included hydrogen production using both existing nuclear power as well as future nuclear development.
- Currently, hydrogen is mainly produced using carbon based thermochemical processes that emit carbon dioxide (CO_2) during production. Electric processes using renewable energy or nuclear power do not emit CO_2, and so these processes are expected to become the primary methods of low carbon hydrogen production in future.

Nuclear hydrogen as an energy carrier

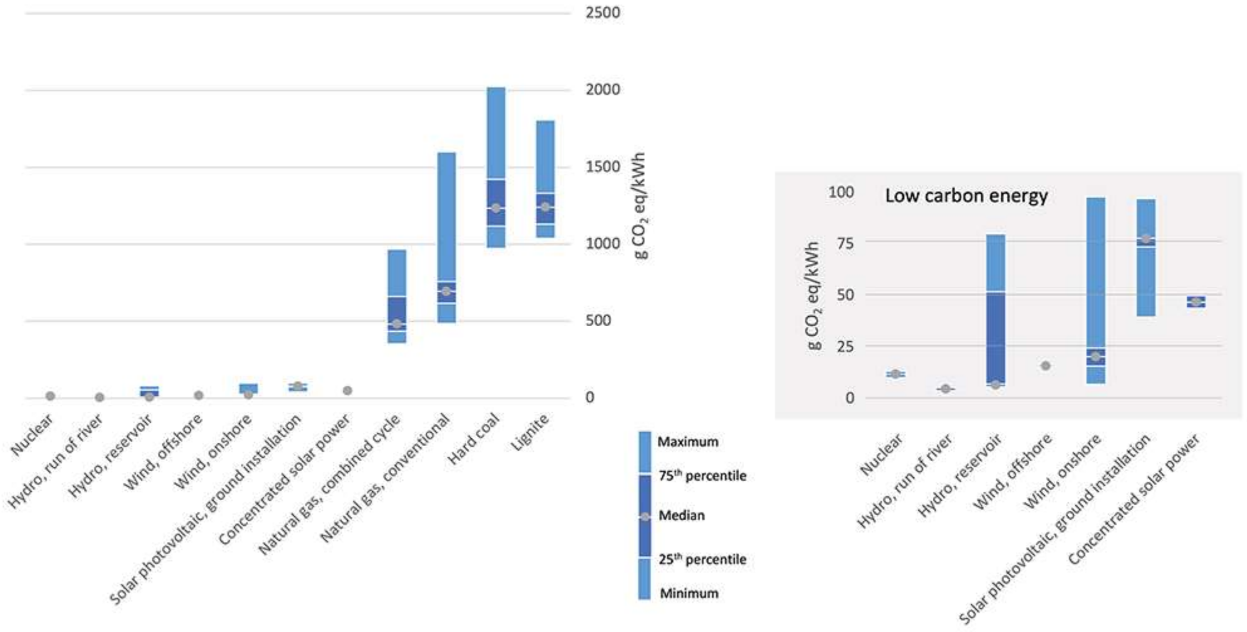
The role of nuclear hydrogen in decarbonization

The energy sector, including electricity and heat, transport, buildings, industry, fuel combustion and fugitive emissions, is responsible for nearly three quarters of global greenhouse gas (GHG) emissions [World Resources Institute, 2020]. Two major undertakings would need to take place simultaneously to reduce global GHG emissions: carbon intensive sectors would need to be electrified wherever possible in terms of technology and economics, and the electricity sector would need to be decarbonized. To achieve climate goals, the power sources in this increasingly electrified world would thus need to shift from fossil fuel to low carbon generation sources, such as nuclear power 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 median CO_2 equivalent emissions per kilowatt hour (kW·h) of energy produced, while solar power releases higher emissions (about 50–75 grams), primarily due to rare earth element compositions.

Because of the increased interest in mitigating global carbon emissions and the difficulty to electrify some sectors, hydrogen’s potential as an energy carrier has been gaining attention. If hydrogen is produced using low carbon energy sources (e.g. nuclear power), it emits almost no CO_2, not only during the use of the hydrogen but also during the production process, as opposed to when hydrogen is produced using other sources of energy (e.g. fossil fuels).

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: adopted from Ref. IAEA [2020].

Efforts to widely deploy hydrogen in the industry, transport and power sectors will support the creation of a decarbonized future. 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), for example, has identified hydrogen and hydrogen based fuels as one of the key pillars of decarbonization (IEA, 2021a). According to the Energy Transitions Commission (ETC), a global coalition of leaders from across the energy landscape working together to accelerate the transition to a zero emissions future, 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 may not be possible or is uneconomic (ETC, 2021). Nucleareurope (formerly FORATOM) considers it essential to adopt all mature low carbon energy sources, including nuclear power, which is capable of producing hydrogen [nucleareurope, 2021].

Nuclear power can provide both electricity and heat 24/7 to support the efficient production of hydrogen through diverse processes. Existing nuclear plants today face the challenge of operating in energy systems with increasing shares of variable renewable energy. Hydrogen provides the option of storing energy and increasing the flexibility of these hybrid systems. In addition, hydrogen produced for external sale could be a valuable alternative revenue stream for nuclear power plants (NPPs) with surplus power.

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

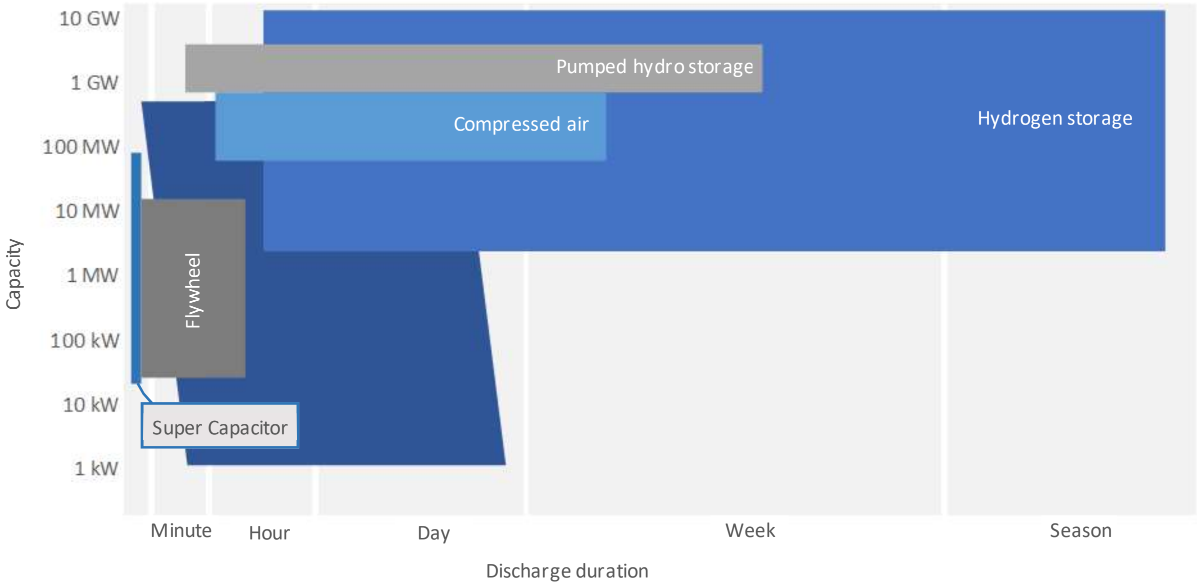
Potential uses of hydrogen

The potential uses of hydrogen as an energy carrier vary widely across many sectors of the global economy. Regional and national nuances will dictate the best use of hydrogen in each country, but some combination of centralized and large scale hydrogen production at NPPs with hydrogen applications in each sector will make an unquestionable contribution on the path 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 currently being used for the production of hydrogen that is then used 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 was used to reduce iron ore there would be no CO_2 emissions.

Transport: Electric vehicles are among the most attractive technologies for decarbonization of the transport sector, but it is not the only way to decarbonize this sector. As a fuel in the transport sector, hydrogen could help drive future decarbonization of large, long distance transport (e.g. shipping and aviation) because hydrogen has a higher energy density than currently commercialized battery storage technologies. It is thus well suited for transport that requires a considerable amount of energy with minimal weight.

Figure 2. Energy storage technologies



Note: MW – megawatt; GW – gigawatt.
Source: adopted 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 is, on the other hand, 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 nearly sixfold from 90 million tonnes in 2020 to 530 million tonnes in 2050 [IEA, 2021a]. 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, 2021a].

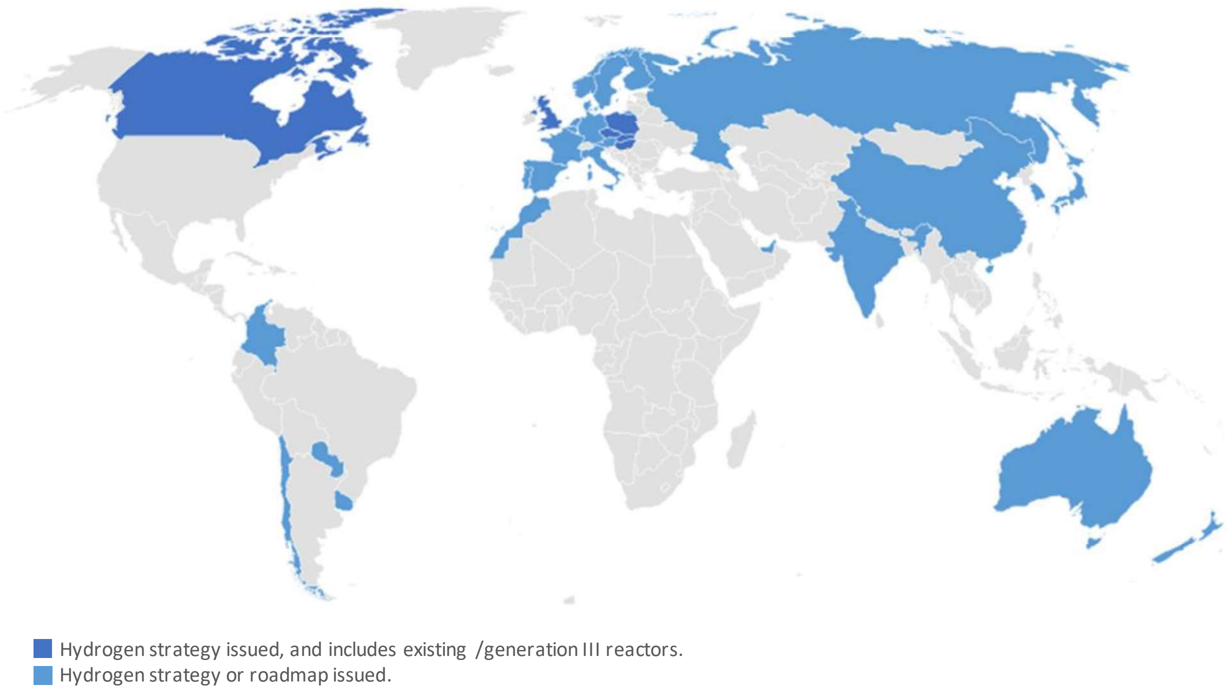
Recent hydrogen policy developments

National interest in hydrogen has grown rapidly in recent years. Figure 3 [HyResource, 2022] shows that several countries have developed comprehensive hydrogen strategies, reflecting their energy needs, environmental goals and economic objectives beyond research and development (R&D) programmes and vision documents. 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.

Some countries mention in their hydrogen strategies the production of hydrogen from existing nuclear

Figure 3. National hydrogen strategies as of June 2022



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

power, as well as hydrogen production from future nuclear developments, such as small modular reactors, and more specifically the high temperature gas cooled reactor (HTGR). These national hydrogen development strategies may offer a promising future for nuclear hydrogen production. The following paragraphs provide specific descriptions of 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 inexpensive off peak electricity from existing NPPs. For example, it mentions that efforts are underway to study the economics of nuclear hydrogen production in Ontario at the Bruce Nuclear Generating Station. However, the country has noted some important infrastructure challenges. Planning documents list, for example, obstacles related to hydrogen deployment at scale, which would 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 non-renewable technologies for power production. The country is therefore considering use of nuclear power for hydrogen production in order to meet its decarbonization goals. It has deemed it much more efficient to equip existing NPPs with large electrolysers and hydrogen storage on-site in an effort to limit energy losses. However, the strategy also mentions that the additional costs and energy losses associated with transporting hydrogen — which is produced using nuclear power or any other power source — to consumption locations also needs to be taken into account.

Hungary [Ministry of Innovation and Technology, Hungary, 2021] needs low carbon hydrogen in the short and medium term to rapidly reduce emissions and establish a viable hydrogen market, but the country is focusing on low carbon hydrogen in the long term. 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 Transdanubian hydrogen ecosystem and North-eastern hydrogen valley, by 2030. In the Transdanubian valley, plans are in place to produce hydrogen using electricity from the Paks NPP to supply hydrogen for the ammonia and refinery industry. There is also potential demand for hydrogen in this region, for example from iron and steel works, as well as from cement production, and thus further increases in hydrogen demand are expected.

Poland [Ministry of Climate and Environment, Poland, 2021] has decided that electrolysis using electricity from NPPs will be one of the technologies used to produce low carbon hydrogen, and that this will be possible after the first NPP unit starts operation, scheduled for 2033. The country considers the most important factor in starting hydrogen production in an NPP is to ensure in advance the conditions for the construction of hydrogen production facilities in the NPP. In terms of the competitiveness of hydrogen production in NPPs, the strategy mentions that it is possible to produce hydrogen on a large scale, and that the costs can be reduced using surplus electricity produced during the night. The country considers that in future it will be possible to produce hydrogen using heat from the HTGR, and it 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 and expeditious manner. For this reason, Slovakia is focusing on hydrogen production using surplus electricity from nuclear power as one method of producing hydrogen.

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 and carbon capture, utilization and storage (CCUS)-enabled hydrogen production, which would ensure that the country supports a 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 hydrogen strategy. The UK expects to learn by producing hydrogen through readily available low temperature electrolysis with existing NPPs during the 2020s, and then expand the range of production technologies to include high temperature electrolysis and thermochemical water splitting from the 2030s onwards so as to enable commercial production at large scale.

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 three main production methods are thermochemical carbon based processes, the electrolytic process and thermochemical water splitting. The former is typically used with fossil fuels and heat, while the latter two processes use water, electricity and/or heat.

Thermochemical carbon based processes

Currently, hydrogen is primarily produced from fossil fuels, which emit 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. When 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 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 thus emit large amounts of CO_2, but these emissions can be reduced through CCUS, or purely through CCS. This process captures and stores CO_2 before it enters the atmosphere. With CCUS, the stored CO_2 is then used for another purpose.

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 or from nuclear power. 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.

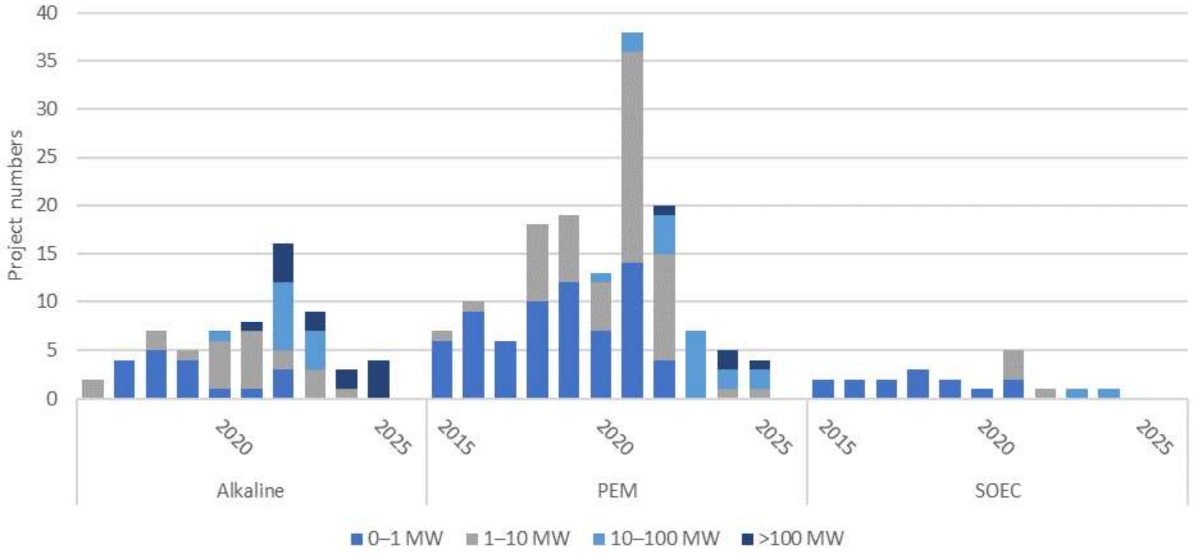
LTEs mainly consist of alkaline electrolysers and proton exchange membrane (PEM) electrolysers. While low carbon hydrogen is getting more attention, the demand for both technologies is increasing, which is ultimately helping each of these technologies to reach commercial scale. Figure 4 [IEA, 2021b] on the following 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.

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].

The alkaline electrolyser is a mature technology used on a commercial scale, with project sizes reaching over 100 MW in 2021. Alkaline electrolysers are characterized by relatively low capital costs compared to other electrolyser technologies, mainly due to the absence of precious materials.

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. They can produce highly compressed hydrogen for decentralized production and storage at refuelling stations and offer flexible operation, including the capability to provide frequency containment reserves and other grid services. 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 currently in R&D. The AEM is a device that changes the proton conductive electrolyte membrane of the PEM electrolyser to an anion conductive material so as 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. Currently, however, there is a durability issue in relation to the electrolyte membrane, and the technological development of highly durable materials is underway.

High temperature electrolysis

High temperature electrolysis uses heat in addition to electricity to produce hydrogen, and thus it is expected to increase efficiency in comparison with low temperature electrolysis. Improvements in efficiency are related more specifically to the temperature of the steam. As the temperature increases, the required proportion of energy for electrolysis that is supplied by heat increases and the supply of energy from electricity decreases, thus enabling electrolysis with less electricity. The Nuclear Industry Association [Nuclear Industry Association, 2021] has reported, for example, that electrolysis taking place between around 600–1000°C requires a third less energy than electrolysis using LTEs. It has also underlined that even with the use of steam at 150–200°C from existing NPPs, efficiency can be expected to improve. In one method, because heat supplied by an existing NPP may not be sufficient to operate the HTE, heat from the nuclear reactor could be used primarily to vaporize water, and the steam after vaporization could then be raised to the HTEs operating temperature range using temperature recuperation, electrical topping heaters or heat pumps. 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. SOECs 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. In order to scale up 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 so as 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, and so the utility has to meet all of the different engineering codes and standards, as well as related regulations. The HTE nevertheless remains an attractive technology for nuclear power, since it can produce both electricity and heat.

Thermochemical water splitting

Water splits into hydrogen and oxygen at temperatures above 4000°C. However, it is difficult to secure such high temperatures, and materials that can withstand such temperatures are limited. One method is under consideration to indirectly split water into hydrogen and oxygen by combining various reactions. Among the different cycles, the sulfur-iodine (S-I) and copper-chlorine (Cu-Cl) cycles are considered to be promising [Suppiah, 2020].

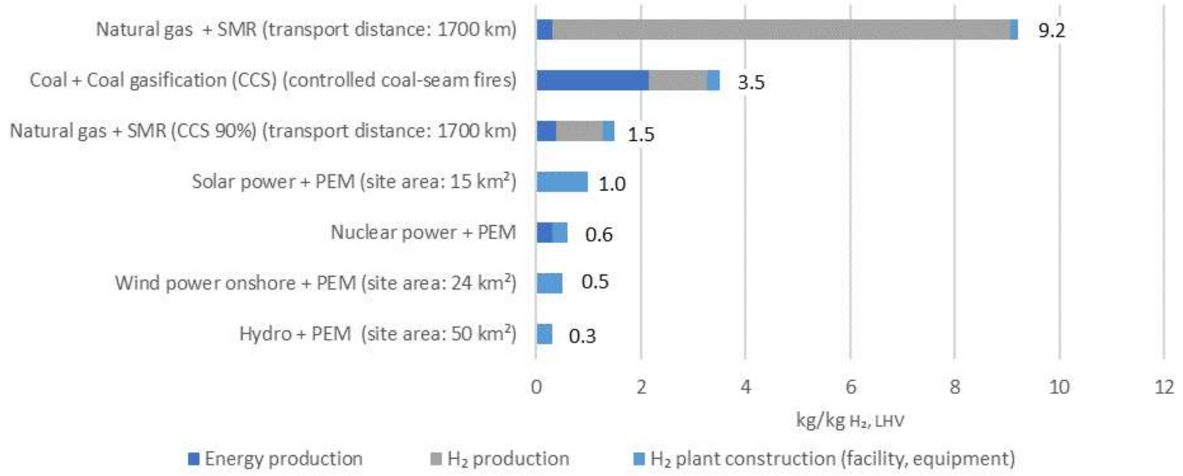
In the S-I cycle, it is possible to decompose water into hydrogen and oxygen with heat at about 900°C. The HTGR design is also suitable for this technology, as it can provide heat of 850–950°C. Hydrogen production via the S-I process was successfully operated for 150 hours in 2019 using test equipment 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 530°C, 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 its own lifetime CO_2 emissions. This information makes clear that adding CCS or using electrolysis can significantly reduce emissions. CO_2 capture rates of CCS are expected to be very high, at about 90%. However, this statistic does not imply that CO_2 emissions can be reduced by 90%, because energy (and the resulting emissions) is required to peform the extraction, capture, transport and sequestration processes. Emissions from natural gas are estimated to be reduced by about 80% over the lifecycle when using CCS. On the other hand, even with such large emission reductions, 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. Solar power's emissions are particulaly large compared with other methods because of the considerable emissions during the production 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.
Source: adapted from Ref. Hydrogen Council [2021a].

2. The business case for nuclear hydrogen

Key points:

- The electrolysis process entails higher costs for hydrogen production than the fossil fuel based process, but electricity accounts for most of the cost of the electrolysis process.
- In order to improve the profitability of hydrogen production, there are several ways to decrease the cost of the electricity used in the production process and to increase the capacity factor of the electrolyser, for example by using electricity from NPPs in long term operation (LTO), or by combining renewable energy and nuclear power.
- Although current hydrogen demand is limited to some sectors, such as oil refining and the chemical industry, it is expected that various sectors, such as long distance transport, steel production and power storage, will also experience increased demand. Cluster projects involving nuclear power have thus been started as a strategy to stimulate such demand.

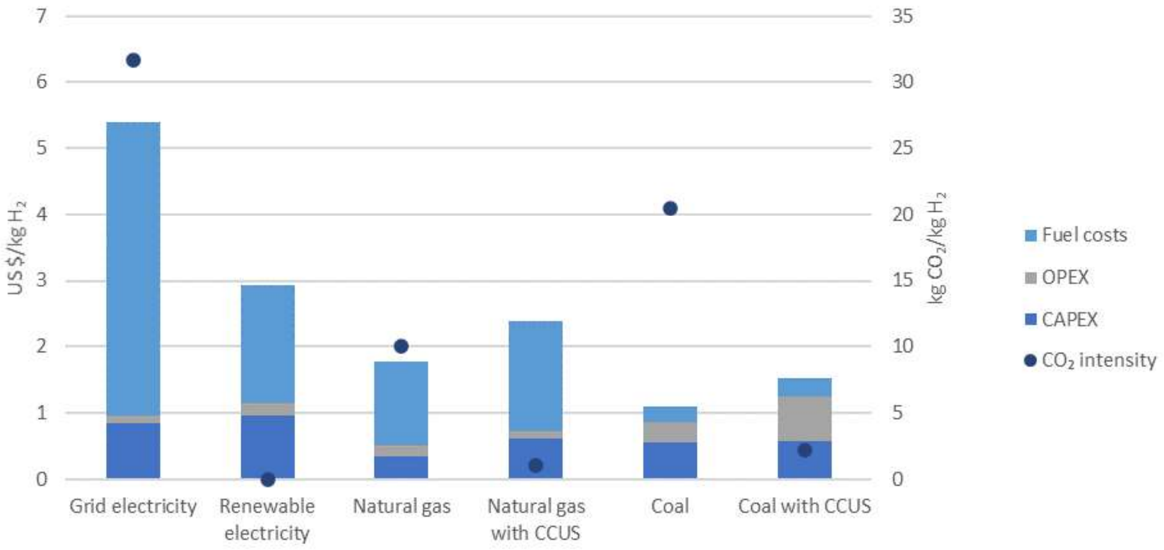
Cost breakdown and revenue maximization

Cost breakdown

Most hydrogen produced in the world today is derived from fossil fuels, through steam reforming of natural gas or the gasification of coal. 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 would also need a sound business case that emphasizes important factors such as cost competitiveness with alternative production technologies.

When discussing the economics of hydrogen, the focus is generally on the cost of production per kilogram (kg). 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 US $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 renewable energy and $5.50/kg using the grid. The differences in cost between the production of hydrogen by electrolysers using renewable energy and its production using natural gas with CCUS is therefore small. One of the main reasons may be that China relies on imported natural gas at relatively high costs and abundant renewable energy resources at relatively low costs (assumed to be $30/megawatt hour (MW·h) in this case). As shown in the breakdown of hydrogen production costs, fuel costs account for a large proportion of the cost of hydrogen production. When hydrogen is produced by electrolysis,

Figure 6. Hydrogen production costs in China in 2018



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

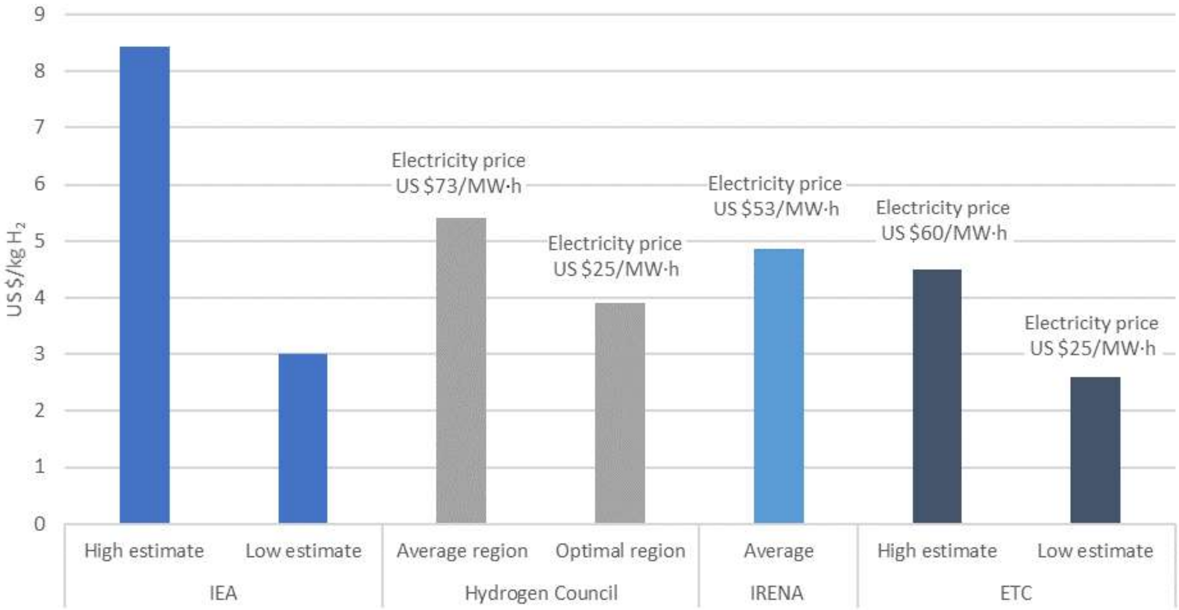
the cost of electricity accounts for a large proportion of the cost, at about 60–80%.

Various publications have outlined the costs of hydrogen production using electrolysis. Since the price of renewable energy differs greatly depending on the region, the cost of hydrogen production using electrolysis has also been shown to differ greatly. It is for this reason that hydrogen production costs are often shown in ranges. As shown in Fig. 7, the IEA has assumed a high case of \$8.50/kgH_2, and the ETC has assumed a low case of \$2.80/kgH_2 [ETC, 2021] (IEA, 2021c) [Hydrogen Council, 2021b] [IRENA, 2020].

Revenue optimization

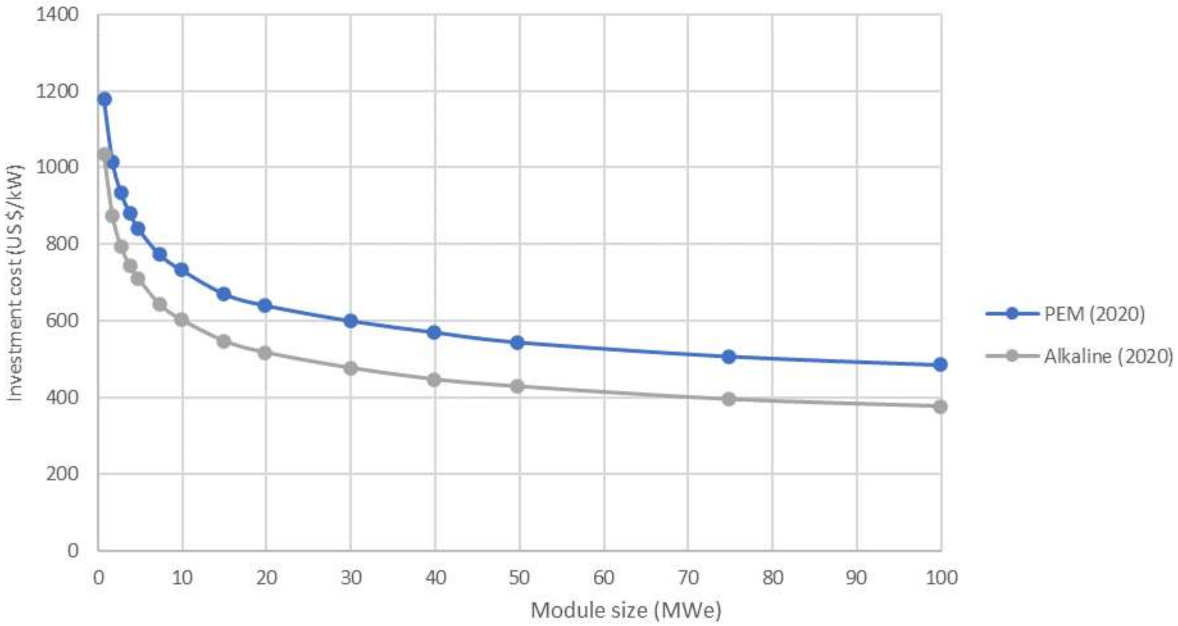
Three main parameters are crucial for the profitability of hydrogen production: (a) capital investment for the electrolyser; (b) the cost of electricity used in the

Figure 7. Hydrogen production costs with electrolysers in 2020



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

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.

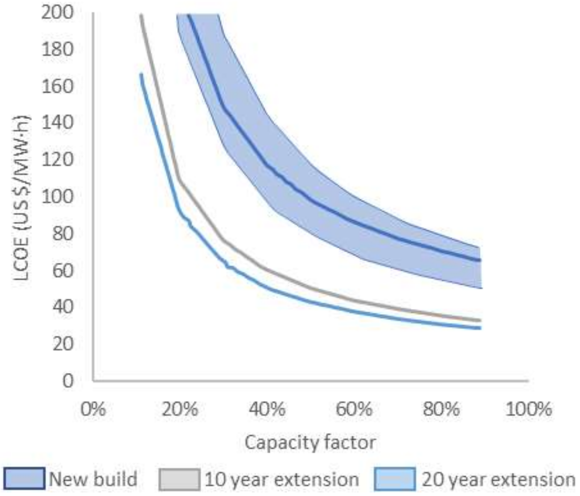
Capital costs

The most expensive component of low temperature electrolysis is not the electrolyser itself but rather all of 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 electrolyser can deliver 10 times the power of a 10 MW electrolyser by adding only about 30–40% of the costs. As a large power generation facility, nuclear plants are well suited for the installation of a large electrolyser.

Electricity costs

The cost of the low emission electricity used by the electrolyser can be further reduced by using low cost 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 energy (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 nuclear plants beyond the typical design life of 40 years. 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. Since, according to the Hydrogen Council and the ETC (see Fig. 7 on page 10), the cost of renewable energy is assumed to be $25–73/kgH$_2$, hydrogen production from nuclear power would be competitive with renewable energy. Therefore, investment in LTO is also beneficial for the production of hydrogen by utilities.

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

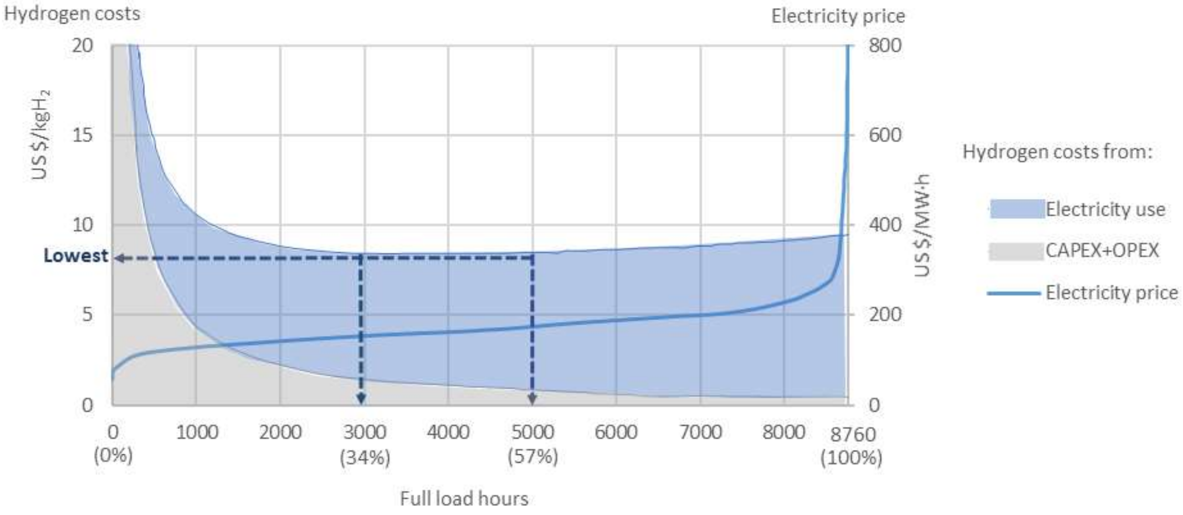


Source: adopted from Ref. IEA & NEA [2020].

Achieving a hydrogen production cost of $1/kgH$_2$, which is the 2030 target of the United States Department of Energy (DOE) Hydrogen Energy Earthshot (or 'Hydrogen Shot' initiative, is equivalent to an electricity price of $20/MW·h without capital expenditure (CAPEX) or operational expenditure (OPEX) [Satyapal, 2021].

In order 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

Figure 10. Hydrogen costs from electrolysis using grid electricity



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

from new construction in that operation and maintenance (O&M) account for a large proportion of the cost in the case of LTO. It is therefore important to reduce the cost of O&M, as well as that of investment.

Capacity factor

The potential exists to use the surplus power in power systems with an increasing share of variable renewable energy to produce low cost, low carbon hydrogen. However, if this surplus power is only available occasionally, it cannot be reliably depended upon to keep costs down. Figure 10 (IEA, 2019) on the previous page shows that the longer the electrolyser runs, the greater the impact of 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, 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 as a result of 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 be competing, in reality they are not. All of these methods and technologies complement each other and are necessary to achieve carbon neutrality by 2050. Hydrogen production from existing nuclear power is not an exception as it is vital to utilize a wide array of production methods.

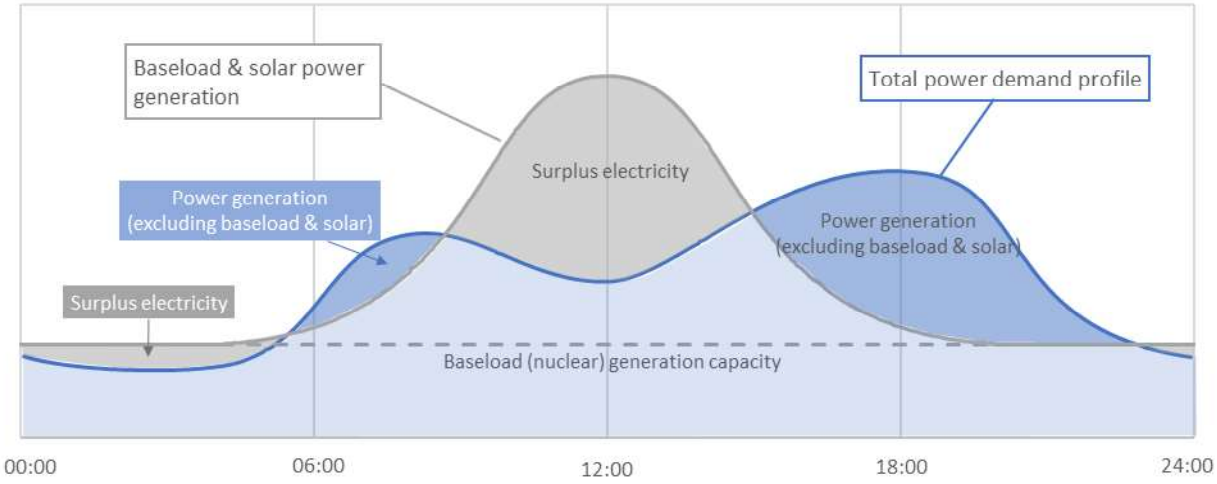
Nuclear power has the advantage of producing electricity in a stable manner, which is useful for continuous hydrogen production and for increasing the capacity factor of the electrolyser. As shown in Fig. 11 [INL, 2017], using nuclear power during the night, when both demand and electricity prices are 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 the refining and chemical industrial 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. To create a decarbonized economy, it will nevertheless be vital to both replace existing cases of hydrogen use with low carbon hydrogen, as well as 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].

focus on expanding hydrogen use to new sectors. As shown in Fig. 12 [ETC, 2021], the ETC groups the potential uses of hydrogen in a zero carbon economy into four categories, depending on the ease of introducing hydrogen utilization into existing systems.

Potential hydrogen demand can be broadly categorized into existing hydrogen and new hydrogen demand. New hydrogen demand can be further subdivided into demand expected in the near future, 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.

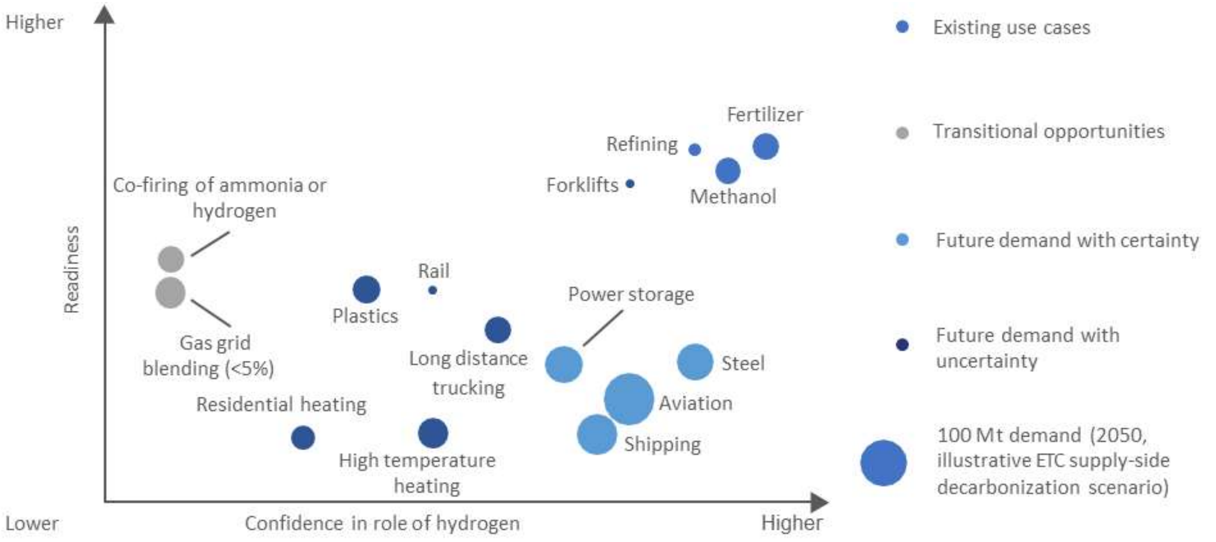
Transitional opportunities include co-firing hydrogen in gas power plants, co-firing ammonia in coal power plants and blending low levels of hydrogen into existing natural gas pipelines. It would be relatively easy to start such endeavours with small amounts of hydrogen as most technical challenges have been cleared. 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.

Future demand with certainty includes steel production, long distance shipping, long distance aviation and power storage. All of these technologies are difficult to electrify and are thus called hard-to-abate sectors, making hydrogen or hydrogen based fuels essential for cost effective decarbonization. Since no other technologies other than hydrogen are currently available, the certainty of demand for hydrogen in these sectors is high, and rapid technological development is underway. It is therefore important to keep a close eye on these sectors.

Future demand with uncertainty includes fuel cell transport, such as long distance trucking, rail and forklifts, residential 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 to electrification or other options. Therefore, it is not clear at this time whether hydrogen demand will increase in such cases. For example, the technological development of electric vehicles is advancing rapidly, and they have the range to compete with fuel cell vehicles. In addition, heat pumps are by far the most efficient way to provide residential heat, meaning that hydrogen has a limited range of applications in this regard. Also, the use of heat in the industrial setting is limited given its flame characteristics. Furthermore, 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.

Numerous R&D and demonstration projects are ongoing for each of these applications. The decision on which type of demand to target will reflect the goals of the project and the characteristics of different regions and markets.

Figure 12. Potential use cases of hydrogen



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

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. In order 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 geographic locations and regional circumstances. In general, however, a focus on cluster based development can provide hydrogen producers with greater certainty in terms 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 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.

Refining and fertilizer clusters are the most hydrogen intensive industries at the moment. Since these sectors share gas supply systems and exchange intermediate products, plants are frequently co-located. Currently, such industries are initiating several projects to use hydrogen produced from renewable energy, 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. A number of 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 building heat could therefore develop as a result. This cluster has the potential to be in large demand, and some feasibility studies are currently underway.

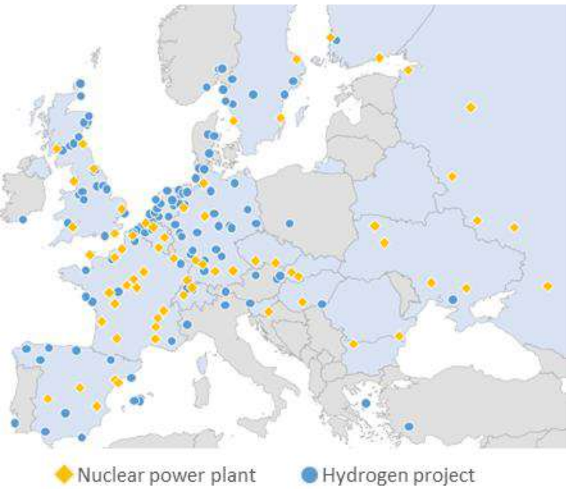
Steel plant clusters have economies of scale in hydrogen demand alone because the large hydrogen demand potential is concentrated in the plant itself. Therefore, facilities are needed that can provide a stable supply of hydrogen in large quantities. Because steel plants are often located in coastal areas, they are likely to be developed as part of port clusters.

Opportunities for growth

Many of the cluster types mentioned above can benefit from existing NPPs across the world. Pillsbury has mapped hydrogen projects around the world [Pillsbury, 2022], and overlaying existing NPPs on this map shows that, in many places, NPPs and hydrogen projects overlap.

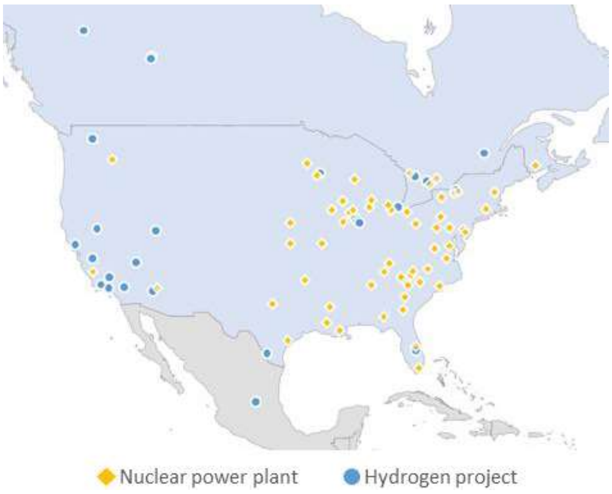
For example, Fig. 13 [Pillsbury, 2022] shows the location of hydrogen projects and NPPs in Europe. In the UK and Germany, where there are a large number of hydrogen projects, many NPPs are located adjacent to hydrogen

Figure 13. Location of hydrogen projects and nuclear power plants in Europe



Source: Nuclear power plant data adopted from Ref. IAEA [2022] and Hydrogen project data adopted from Ref. Pillsbury [2022].

Figure 14. Location of hydrogen projects and nuclear power plants in North America



Source: Nuclear power plant data adopted from Ref. IAEA [2022] and Hydrogen project data adopted from Ref. Pillsbury [2022].

projects. Also, in countries with a large number of NPPs, such as France, several hydrogen projects are located next to NPPs. Figure 14 [Pillsbury, 2022] on the previous page shows the location of hydrogen projects and NPPs in North America. While most hydrogen projects are currently located on the west coast, the figure shows that there are relatively few NPPs here. On the other hand, most hydrogen projects on the east coast of North America are located near NPPs. The location affinity between NPPs and hydrogen projects is thus high on the east coast. 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 and more efforts are being made to utilize electricity from NPPs in an effort to promote efficient hydrogen production. In the UK and the Russian Federation, hydrogen cluster projects using NPPs to support facilities for hydrogen hubs have already begun to appear, and something similar is being proposed in Hungary's national hydrogen strategy. In the USA, an infrastructure law for clean hydrogen hubs has been launched and includes $8 billion in investment. 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.

3. Utility demonstration projects

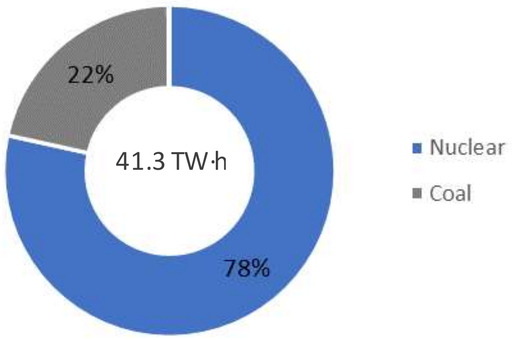
Key points:

- In recent years, small scale projects for hydrogen production using electricity from existing NPPs have been initiated around the world to demonstrate their technical feasibility and economic competitiveness.
- Major nuclear hydrogen projects are underway — five in the North America (Canada: one project; USA: four projects) and four in Europe (Russian Federation: one project; Sweden: two projects; UK: one project) — and the utilities operating the NPPs are acting as core members of these projects.
- By producing low carbon hydrogen, utilities are contributing to the realization of a decarbonized society, as well as to making effective use of electricity while securing new revenue sources.

An overview of demonstration projects

Progress in nuclear hydrogen demonstration projects differs depending on the region of the world. Currently, several projects have started or are preparing to start in North America and Europe, but little progress has been made in Asia at the time of writing this publication Selected nuclear hydrogen demonstration projects from around the world, shown in Fig. 16 and ordered from the most advanced to those in the early stages of research or conception, are outlined in the following paragraphs.

Figure 15. Energy Harbor generation in 2019



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

Energy Harbor (USA)

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

Energy Harbor in the USA operates 3947 megawatt electric (MWe) of nuclear power capacity (comprising four reactors at three sites in the country), supplying about 33 terawatt hours (TW·h) of low carbon electricity from NPPs annually, as shown in Fig. 15. 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 US DOE in the framework of the Advanced Reactor Development Project funding pathway pathway [INL, 2019] [US NE, 2019]. This project met the DOE objective to support innovation in and the competitiveness of the US 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 is planning a two year demonstration project at the Davis-Besse NPP in Ohio, where the company is installing a 2MW LTE skid to produce hydrogen. The demonstration project is expected to begin nuclear hydrogen production in 2024. The LTE is a PEM electrolyser, which consumes electricity from the NPP and produces 800–1000 kg/day H_2. The power will be supplied from behind the meter to reduce the cost associated with transmission. Energy Harbor's objective

Figure 16. Hydrogen production using existing NPPs equipped with electrolysers

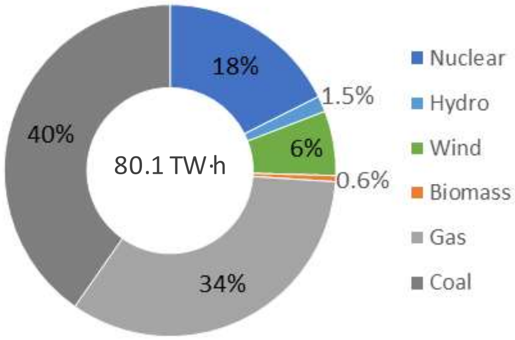
Source: based on data from Ref. IAEA (2022) is to explore the economic viability of hydrogen production in the NPP, and to demonstrate the compatibility and synergy of the two technologies. Potential uses include public transport and steel production. The nuclear plant is located near major hydrogen 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].

The continued operation of the Davis-Besse NPP is dependent on local energy and capacity prices to operate the plant in a cost effective manner. Production of nuclear hydrogen at the plant could provide a new source of revenue to improve overall economics.

Xcel Energy (USA)

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

Figure 17. Xcel Energy generation in 2019



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

Xcel Energy in the USA has set a target of delivering carbon free electricity by 2050, and as Fig. 17 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), a highly efficient process that will use steam and electricity from the Prairie Island NPP in Minnesota. More specifically, a solid oxide type electrolyser will be combined with the NPP to extract the steam generated during normal nuclear operations and use heat in an effort to lower the amount of power required for the electrolyser, resulting in lower electricity consumption on the part of the electrolyser.

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 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. Hydrogen produced by the demonstration project is being evaluated for use at the power plant or at Xcel Energy's other NPP (Monticello). Because of 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.

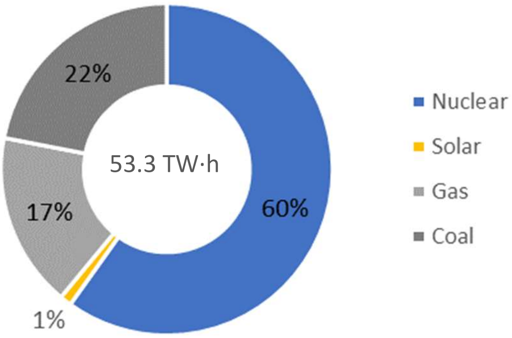
Xcel Energy conducted a technoeconomic analysis with Idaho National Laboratory (INL), the Argonne National Laboratory (ANL) and the National Renewable Energy Laboratory (NREL) and the Electric Power Research Institute (EPRI) of the potential hydrogen demand around NPPs and of optimal hydrogen production with the HTSE using electricity from NPPs [INL, ANL, NREL, EPRI, Xcel Energy, 2021]. The analysis identified the hydrogen market, including ammonia production, which should be targeted in terms of the CO_2 emission reductions required for each application in the vicinity of the Prairie Island and Monticello NPPs. It also identified the target electricity price for hydrogen produced with the HTSE and NPPs so as to be competitive with steam methane reforming, and underlined that a large CO_2 credit will be required given the unlikelihood of significant reductions in NPPs O&M costs. Additionally, the analysis considers the optimal combination of HTSE capital expenses, HTSE capacity and a possible hydrogen production tax credit to ensure profitability compared to a business as usual case. It also notes the importance of identifying hydrogen demands, along with the required delivery requirements that will drive hydrogen storage requirements and overall project costs.

In 2020, the DOE provided approximately $14 million in funding for the project [INL, 2020] [US NE, 2020], which is expected to start hydrogen production in 2024.

APS and PNW Hydrogen (USA)

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

Figure 18. APS generation in 2019



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

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 Fig. 18, it generates more than 32 TW·h annually, contributing to the production of clean energy. APS recently 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 cost of capacity from co-firing hydrogen in a peaking natural gas fired turbine electricity generator compared favourably to the capacity 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 capacity demonstration project beginning in 2022. The size of the electrolyser will be approximately 17 MW. A compression and storage system will also be installed. PNW Hydrogen is seeking to use surplus nuclear energy during hours when renewable production is high so as to produce hydrogen. The electrolyser will produce hydrogen when electricity demand is low, and the stored hydrogen will then be used to supply electricity during peak demand at times when solar energy resources are not available and energy reserves are low. The objectives of the demonstration project are 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].

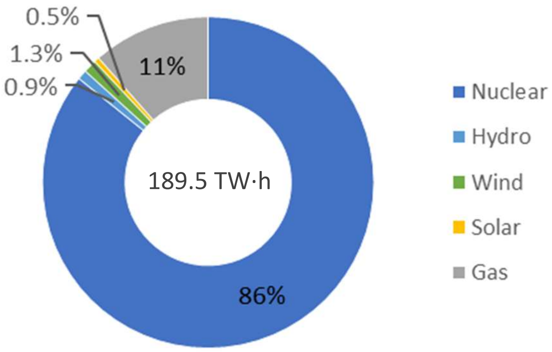
The amount of electricity generation by solar energy in Arizona, where APS's Palo Verde NPP is located, began to increase in 2012, and by 2020 the amount reached about 6 GW·h, accounting for 5% of total electricity generation in Arizona. Across the rest of the southwestern USA, solar power generation is booming. The rapid deployment of solar power in California is attributed to its 100 Percent Clean Energy Act of 2018, which sets interim targets of 60% of total retail sales of electricity from renewable energy by 2030 on the path towards 100% carbon free electricity in the state by 2045.

Within California, the amount of solar electricity generation in 2020 was about 31 GW·h, accounting for about 16% of total electricity generation. APS's Palo Verde NPP has access to the California power market, making the state an attractive off taker of stored energy when demand peaks in late afternoon hours. In a power market dominated by solar power, as is the case in California, the ability to also use hydrogen for energy storage is very attractive and worth demonstrating.

Constellation Energy (USA)

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

Figure 19. Constellation Energy generation in 2019



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

Constellation Energy (formerly Exelon's power generation business) is one of the largest NPP operators in the USA. As shown in Fig. 19, more than 90% of annual output emanates from nuclear and wind, helping to accelerate the transition to a carbon free future. Constellation Energy plans to demonstrate the production, storage and use of hydrogen in existing NPPs. The project began in 2020 and will have a project duration of three years (becoming operational by the end of 2022), with a budget of $14.4 million. It will receive up to $5.6 million in funding as part of the DOE H2@Scale project [Exelon, 2021a].

The project is a collaboration between Constellation Energy, NREL, Nel Hydrogen (a Norwegian Nel ASA subsidiary), INL and ANL. A 1.25 MW PEM electrolyser will be installed on-site. Constellation Energy plans to explore dynamic operation of the electrolyser.

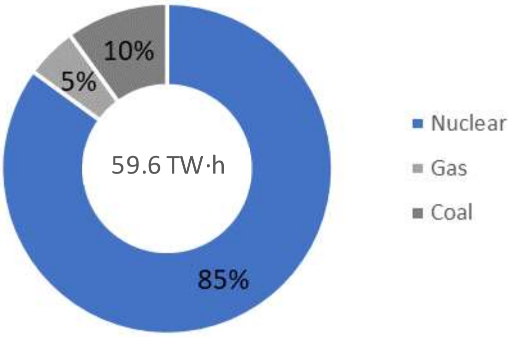
The project will provide an in-house supply of hydrogen for nuclear power generation to eliminate the need to rely on external suppliers. Hydrogen produced in the demonstration project will be used as a cooling gas for the plant's generator in order to reduce the O&M costs of the plant, and ensure chemistry control for the plant components. Future hydrogen applications include injecting the hydrogen into gas pipelines and selling it to the local hydrogen market. In anticipation of this use case, a demand study of the hydrogen market near NPPs is also being included in the project.

Constellation Energy operates 21 497 MWe of nuclear power capacity, comprising 21 reactors at 12 facilities across Illinois, Maryland, New York and Pennsylvania. Because of 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, based on technical and business factors [Exelon, 2021b]. Technical factors include the site's electrical, mechanical, land 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.

EDF Energy (United Kingdom)

EDF Energy is generating low carbon electricity from wind, solar and nuclear to help cut UK carbon emissions to zero. As shown in Fig. 20, 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 20. 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)

EDF Energy received funding from the UK government to carry out a hydrogen production project at the Heysham NPP so as to forge the way towards production of low carbon hydrogen on a large scale [EDF Energy, 2019]. In Phase 1, the utility worked with Lancaster University, the European Institute for Energy Research and the Atkins consulting firm 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, producing 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. The technical viability of hydrogen production in combination with NPPs was confirmed via a feasibility study and via conceptional design, both of which confirm that production meets the requirements of nuclear safety and industrial regulations.

Since a hydrogen production system that uses a combination of nuclear power and electrolysis can be replicated at other EDF Energy NPPs, it was also concluded that scaling up of the electrolyser will enable hydrogen to be supplied on a large scale in order to meet the UK's future hydrogen demand.

If utilized to an annual capacity factor of 95%, through stable nuclear power and oxygen as a by-product of the Heysham NPP, the cost of producing hydrogen could be reduced to a level comparable to steam methane reforming with CCS.

The project has not proceeded to the demonstration stage as a result of challenges in developing a successful business model without production subsidies or incentives for end users to consume the hydrogen produced [Nuclear Industry Association, 2021].

Sizewell power stations

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

NPP: Sizewell C Power Station
EPR (3200 MW)
Location: Leiston, Suffolk, UK
Electrolyser: HTE (capacity to be determined)

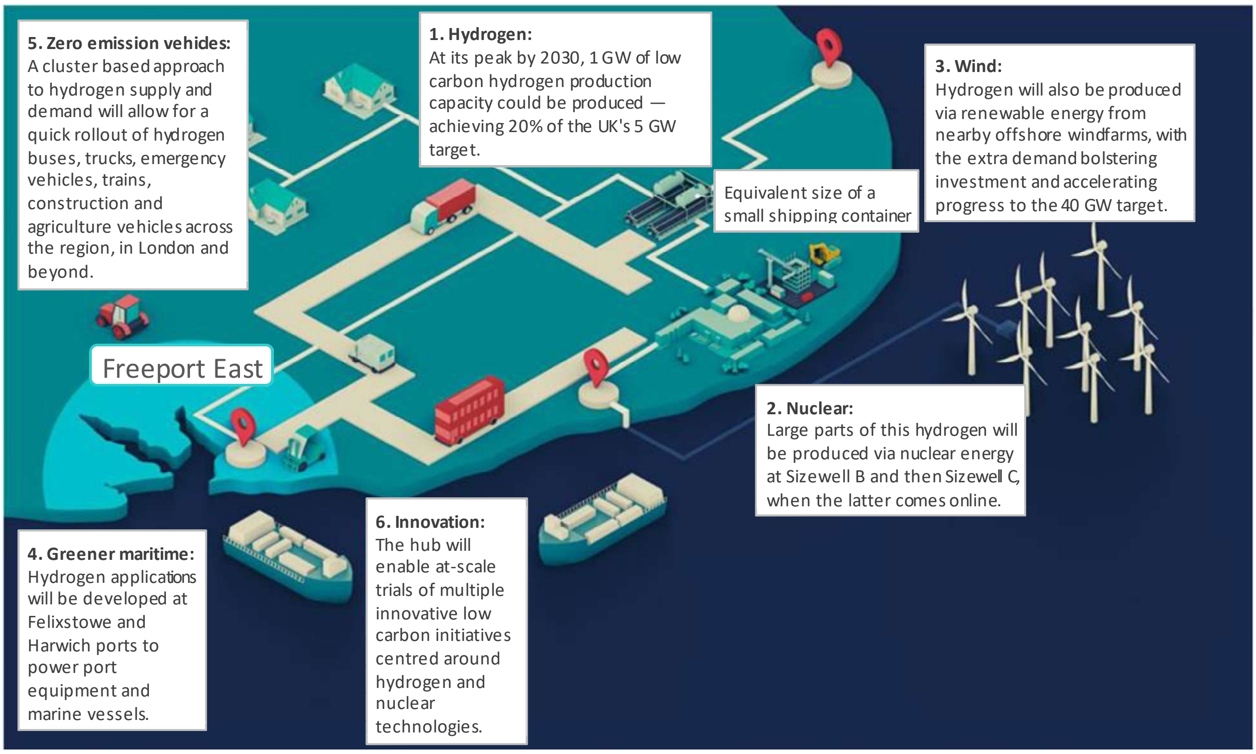
EDF Energy is exploring hydrogen production at the site of the Sizewell B NPP to help contribute to the net zero ambitions of the UK [EDF Energy, 2022]. The utility plans to install a 2 MW electrolyser in 2022 and begin producing up to 800 kg/day H_2 using electricity from the Sizewell B NPP [EDF Energy, 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.

Further applications include the potential to supply hydrogen to local government, nearby ports, industry and local bus and rail transport. In such cases there is a potential to scale up production to meet demand. The future potential of the project to produce hydrogen from the Sizewell C NPP will also be evaluated throughout the demonstration phase.

An electrolyser at the Sizewell C NPP would have the potential to use some of the electricity and heat at the site to produce low carbon hydrogen more efficiently. The Freeport East project, which would include the Sizewell C NPP, was announced as one of eight new freeports in 2021, and is intended to be a hub for global trade, as shown in Fig. 21 [Freeport East, 2022]. Freeports are designated areas that are eligible for a wide range of special regulatory requirements, tax relief and government support. They are specifically designed to encourage companies to import, process and re-export products.

Sizewell B and Sizewell C nuclear power stations are expected to produce hydrogen as part of an energy hub that will support this freeport. Freeport East's plan is to install a 1 GW electrolyser by 2030 to produce 145 000 tonnes of hydrogen, which would supply cargo, public transport, ships, aviation, industrial processes and district heating. Given the presence of many offshore wind farms in the area surrounding Freeport East, the development of a hydrogen hub will be promoted in cooperation with the wind farms in order to balance the variable electricity production. This scheme contributes to six of the UK’s Ten Point Plan for a Green Industrial Revolution (i.e. hydrogen, nuclear, wind, a greener maritime, zero emission transport and innovation) [Government of UK, 2020].

Figure 21. Freeport East Hydrogen Hub



1. Hydrogen: At its peak by 2030, 1 GW of low carbon hydrogen production capacity could be produced — achieving 20% of the UK's 5 GW target.

Equivalent size of a small shipping container

2. Nuclear: Large parts of this hydrogen will be produced via nuclear energy at Sizewell B and then Sizewell C, when the latter comes online.

3. Wind: Hydrogen will also be produced via renewable energy from nearby offshore windfarms, with the extra demand bolstering investment and accelerating progress to the 40 GW target.

4. Greener maritime: Hydrogen applications will be developed at Felixstowe and Harwich ports to power port equipment and marine vessels.

5. Zero emission vehides: A cluster based approach to hydrogen supply and demand will allow for a quick rollout of hydrogen buses, trucks, emergency vehicles, trains, construction and agriculture vehicles across the region, in London and beyond.

6. Innovation: The hub will enable at-scale trials of multiple innovative low carbon initiatives centred around hydrogen and nuclear technologies.

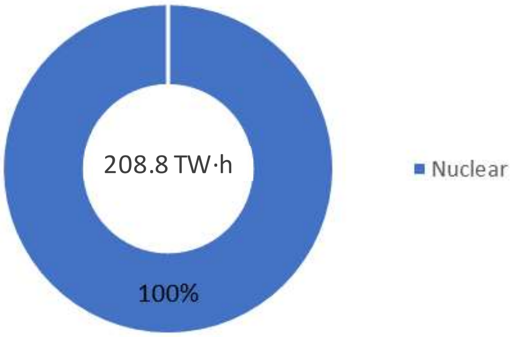
Source: adopted from Ref. Freeport East [2022].

Thus far, the feasibility of different steam tapping points, their impact on the plant design and the trade-offs of using a part of the steam to produce hydrogen have been evaluated. A decision on whether to incorporate flexible operation and design in the energy hub are challenges that would need to be addressed in future.

Rosatom (Russian Federation)

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

Figure 22. Rosatom generation in 2019



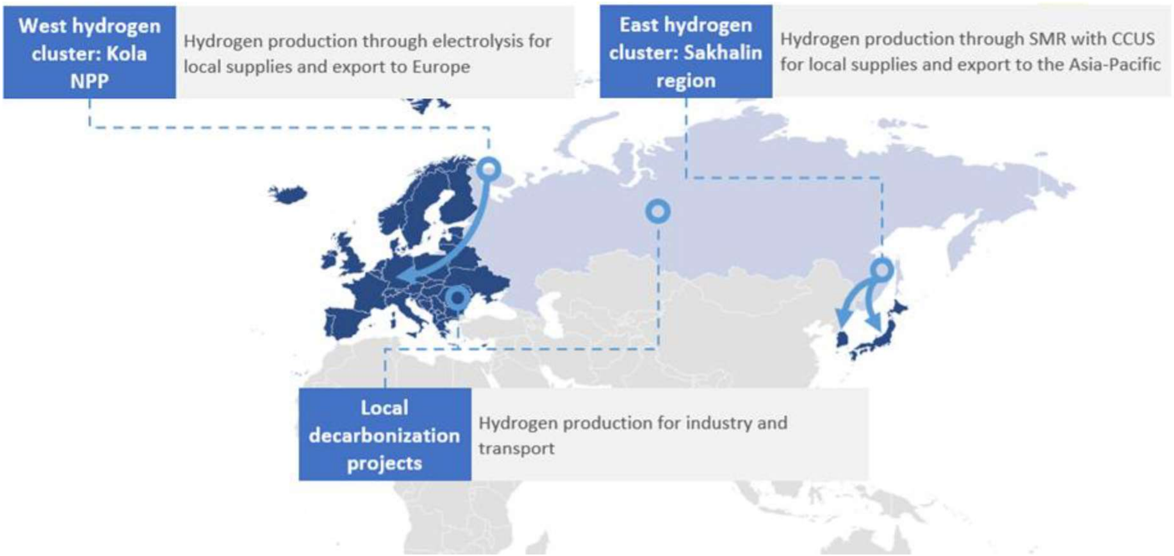
Source: based on data from Ref. Rosatom [2022].

As shown in Fig. 22, Rosatom generates about 200 TW·h of nuclear power, making it the first source of energy in the Russian Federation in terms of electricity power generation, and representing around 20% of the total power generated in the country. Rosatom has been carrying out extensive research on hydrogen production since 2018, with priority being given to the development of water electrolysis using existing NPPs, as well as steam methane reforming using the HTGR.

For hydrogen production using existing NPPs, the country plans to develop and demonstrate the production and storage of hydrogen at the Kola NPP and then to further scale up this production and storage. In future, the technology from this demonstration project will be used to deploy hydrogen production facilities at other NPPs. This project involves the construction and commissioning of a hydrogen production facility using proprietary designed anion exchange matrix electrolysis units (initial capacity 1 MW), and will begin producing hydrogen in 2025 [Rosatom, 2021a]. In order to make effective use of the resources at the Kola NPP, consideration will be given to the use of surplus energy and the infrastructure facilities used to produce small amounts of hydrogen.

In addition, the project is being strongly promoted as part of the Development of Hydrogen Energy in the Russian Federation until 2024 Plan [Government of Russian Federation, 2020a] and 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) being to establish hydrogen

Figure 23. Potential locations for hydrogen industrial clusters and hydrogen pilot projects in the Russian Federation



Source: adopted from Ref. Rosatom [2021b].

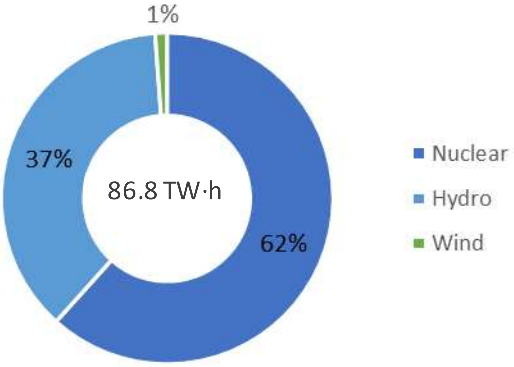
clusters, such as the West hydrogen cluster, which will include the Kola NPP as shown in Fig. 23 [Rosatom, 2021b] on the previous page.

The hydrogen produced in these clusters will not only be used to decarbonize domestic industry, transport and energy sectors, but also to be exported to Europe from the West hydrogen cluster and to the Asia-Pacific region from the East hydrogen cluster. In its energy planning documents, the Russian Federation outlines its aims 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].

Vattenfall (Sweden)

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

Figure 24. Vattenfall generation in Sweden in 2019



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

Vattenfall owns 5485 MWe of operating capacity (comprising five reactors) located in Sweden. As shown in Fig. 24, nuclear generation represented around 62% of Vattenfall's total electricity in Sweden in 2019. Vattenfall has been producing hydrogen using electricity from the Ringhals NPP since 1997 [Vattenfall, 2018]. The LTE electrolyser has a capacity of 0.8 MW and normally produces 60–110 m^3/hour hydrogen. The hydrogen produced is used to cool nuclear generators. Vattenfall does not currently have any projects to expand or develop hydrogen production on-site at the Ringhals and Forsmark NPPs.

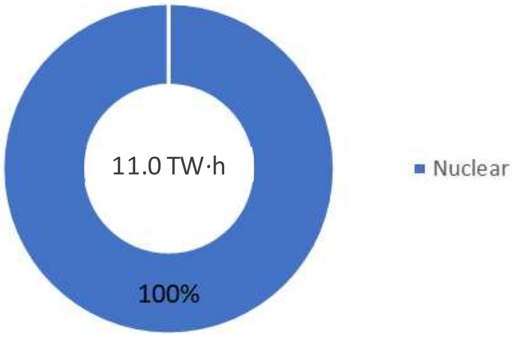
However, Vattenfall is applying this experience in a pilot study with Preem, the largest oil company in Sweden, to produce hydrogen using electricity from a power grid in Gothenburg [Vattenfall, 2021a]. Vattenfall sells only nuclear, hydro, wind and minimal amounts of biomass electricity in Sweden, and 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 is underway to move to the next phase in 2022.

Vattenfall has also established the Hydrogen Breakthrough Ironmaking Technology (HYBRIT), a joint venture with the Luossavaara-Kiirunavaara AB (LKAB) mining company and Svenskt Stål AB (SSAB) steel, which together have been working on a hydrogen based steelmaking process since 2016 [Vattenfall, 2021b]. The project is targeting completion by 2035. 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 — also began, with the goal of completion by 2022 [Vattenfall, 2021c]. In July 2021, Vattenfall delivered to the car manufacturer, Volvo, the world's first steel produced using the HYBRIT technology. The production process involved the use of 100% fossil free hydrogen rather than coal and coke [Vattenfall, 2021d]. In 2026, the transition to 1.3 million tonnes of plant scale production is planned to begin at a demonstration plant in Gällivare, in northern Sweden, and production is planned to increase to 2.7 million tonnes by 2030.

OKG (Sweden)

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

Figure 25. OKG generation in 2019



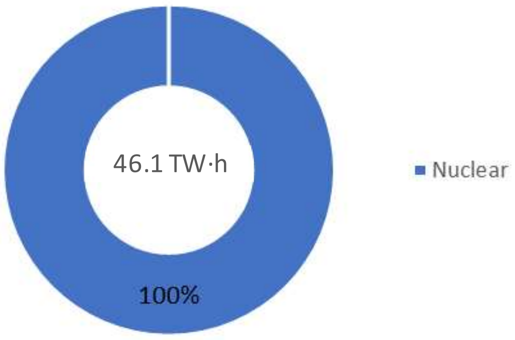
Source: based on data from Ref. IAEA [2022]

OKG Aktiebolag (OKG) owns only one reactor that produces electricity, 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 Fig. 25. OKG signed a contract in 2022 to supply hydrogen produced at the Oskarshamn NPP to the industrial gas company, Linde Gas [OKG, 2022]. At the Oskarshamn NPP, hydrogen is produced using electricity from the NPP and has been used for the cooling of generators since 1992. The 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 currently has some overcapacity. Although the amount of hydrogen produced with this excess capacity is relatively small, the company expects the demand for hydrogen to increase in the future, and it is thus essential to expand 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, is currently underway.

Bruce Power (Canada)

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

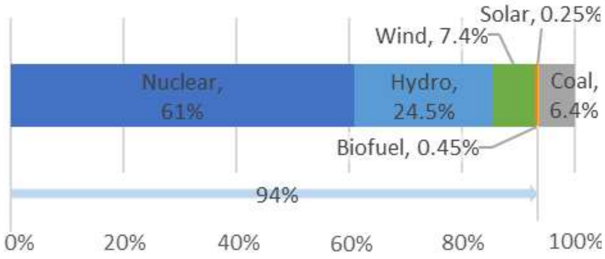
Figure 26. Bruce Power generation in 2019



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

Bruce NPP total capacity is 6358 MWe (comprising eight units) and is one of the largest NPPs in the world. As shown in Fig. 26, 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.

Figure 27. Ontario's electricity production in 2019



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

As a result, more than 90% of Ontario's electricity is generated by nuclear, hydro and renewable energy sources (see Fig. 27), and thus Ontario could potentially have a global competitive advantage in producing low carbon hydrogen. In fact, there is sufficient demand for hydrogen in Ontario from the oil refining and chemical industries, as well as for home heating. The above factors make Ontario an ideal place to start a hydrogen project.

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]. The project will be undertaken in collaboration with the renewable fuels manufacturer, Greenfield Global; with Hydrogen Optimized, which has the high current unipolar water electrolysis system technology; and with the agricultural company, Hensall Co-op. The project is expected to be completed in early 2023.

4. Status of other countries with nuclear power plants

Key points:

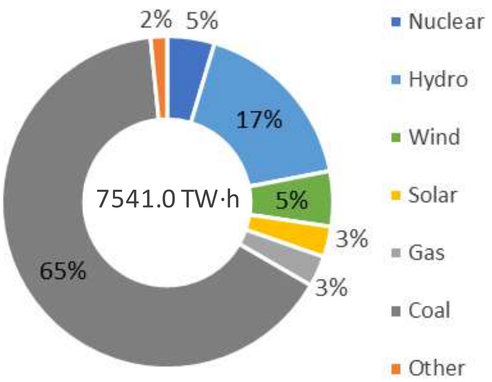
- While there are many existing nuclear power plants in Asian countries, very few have associated hydrogen production projects using the electricity from these plants, mainly due to the large share of fossil fuels and the small share of low carbon energy in net generation.
- China and Japan are nevertheless actively engaged in R&D for more efficient hydrogen production using electricity and heat, or only heat, from the high temperature gas cooled reactor. They are thus leading the region in efforts to combine next generation nuclear reactors and hydrogen.

Overview of other countries

Although neither China or Japan have initiated projects to produce hydrogen with existing nuclear plants, both countries have started advanced reactor development and have realized prototype construction for non-electric energy markets, including for hydrogen. Korea, which, similar to China and Japan, has many NPPs, has begun to consider hydrogen production using the HTE and nuclear power. Other countries have also expressed an interest in nuclear based hydrogen production, although none have active projects ongoing.

China

Figure 28. China generation in 2019



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

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 so as to help balance the country's power system [CNNC, 2021]. The CNNC also hopes to provide low carbon hydrogen to local governments in order to support emission reductions.

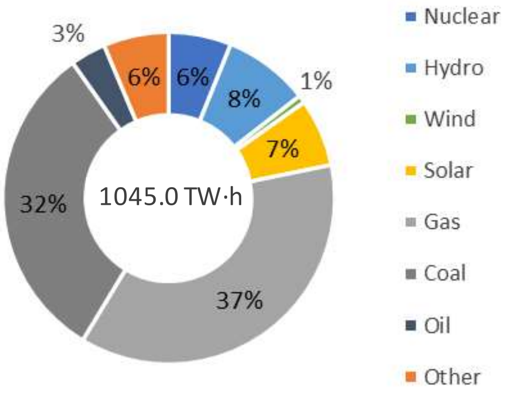
In 2021, China completed construction of a demonstration HTGR at the Shidao Bay Nuclear Power Plant in northeast China's Shangdong province [World Nuclear News, 2021]. The development of an HTR capable of highly efficient power generation and hydrogen production has been emphasized by the Chinese government and is receiving long term support [Tsinghua University, 2010]. In addition to electricity, markets for non-electric products are also being targeted through this project, including hydrogen.

The CNNC has been conducting research on hydrogen production from nuclear power. At present, under the influence of China's zero carbon policy, the load factor of nuclear power as a clean energy is on the rise, and the economic viability of nuclear power generation is improving. On the other hand, China's hydrogen energy industry is not fully mature, with local demand for hydrogen energy unclear and the cost of hydrogen production using electricity from nuclear power relatively high, making it less economical to produce hydrogen from nuclear power than to generate electricity. As can be seen in Fig. 28, 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.

At the same time, hydrogen production from renewable energy, for example from a solar photovoltaic farm located nearby a chemical plant, is making progress. Hydrogen production from renewable energy in China is considered to be more flexible in terms of location and demand, and the price is expected to lower in future compared with nuclear hydrogen production [CNNC, 2021].

Japan

Figure 29. Japan generation in 2019



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

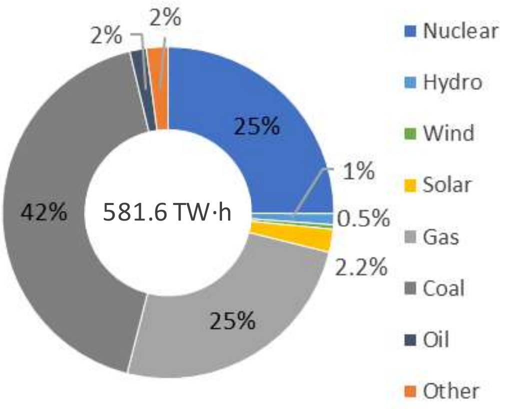
Japan has 31 679 MWe of operable nuclear power capacity (comprising 33 reactors) and was one of the first countries to develop a national hydrogen strategy. In 2021, the Japan Atomic Energy Agency (JAEA) restarted the High Temperature Engineering Test Reactor (HTTR), a 30 MW experimental HTGR in Oarai, Japan [JAEA, 2021b], and from 2022, the JAEA and Mitsubishi Heavy Industries started 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 and equipment modifications and tests will be carried out step by step to connect the HTTR to a hydrogen production facility using the steam methane reforming process. The technologies used for connection purposes will be confirmed up to around 2030. In the interim, the agency is also developing low carbon hydrogen production technologies that include an S-I cycle, and these low carbon hydrogen production 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.

On the other hand, no hydrogen production projects using existing NPPs currently exist in Japan. Although 9486 MWe of nuclear power capacity (comprising ten reactors) have been restarted since the accident at the Fukushima Daiichi NPP, the share of fossil fuel in Japan's electricity mix is still large (see Fig. 29 on page 24). 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, nuclear plants 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 costly international markets, and geographic and weather conditions are not ideal for 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 in order to secure a stable supply. Agreements have already been signed with Australia in this regard, and projects are thus underway.

Korea, Republic of

Figure 30. Korea generation in 2019



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

In **Korea,** a national project has started to produce hydrogen using electricity and high temperature steam from existing nuclear power, accounting for about a quarter of net generation (see Fig. 30). The project is planned to take place near the Hanul NPP site in Uljin [The Korea Electric Times, 2022]. As for the project schedule, it will start with the demonstration of hydrogen production using the 5 MW class LTE and the 50 kW class HTE in phase 1 and then gradually move to commercial hydrogen production with the 100 MW class 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. One of the key points for cost reduction is how to add heat for HTE operation, which is insufficient using the heat from existing NPPs. Along with demonstration at an existing NPP, the design and utilization plan for the HTGR are included in the project in order to help resolve this challenge.

A memorandum of understanding for the project has already been signed between Uljin County, Seoul National University and 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].

Additional countries considering nuclear hydrogen production

Other countries around the world are also considering nuclear hydrogen production, but their projects are in much more nascent development stages. The nuclear hydrogen 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 United Arab Emirates (UAE) and France.

At the Angra NPP in **Brazil**, sodium hypochlorite is produced from sodium chloride and water using an electrolysis system for sterilization to prevent pipe corrosion by microbiotas in the seawater that is used for cooling the tertiary loop. 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 future. The hydrogen will be used as fuel for fuel cells, power plants and hydrogen vehicles. The company has developed a partnership to conduct 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 Program (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 60% [National Atomic Energy Commission of Argentina, 2021].

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 2050 Net Zero goal but that it can also support world decarbonization through hydrogen export. The Emirates Nuclear Energy Corporation (ENEC) notes that once all 5452 MWe (four reactors) of Barakah NPP are operational, it will contribute significantly to the electricity supply, as well as to hydrogen production for decarbonization in the UAE [ENEC, 2021a]. Currently, two reactors are in operation and two reactors are under construction. 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 announced a five year investment plan called France 2030, which includes two electrolyser giga factories by the end of the decade [Government of France, 2021]. France aims to become a leader in hydrogen production by 2030 through this plan, producing low carbon hydrogen in its own country instead of relying on imports. To achieve this aim, the investment is expected to reach €2.3 billion. 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 nuclear plants could be a major asset [Dalton, 2021].

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 and 3 billion of investment [EDF, 2022]. The group considers that the challenge is to produce hydrogen as close as possible to the demand site in order to reduce hydrogen transport costs. Since more than 90% of electricity generation in France comes from nuclear power and renewable energy, it is possible to produce low carbon hydrogen by connecting electrolysers to the grid, making it relatively easy for France to meet this challenge compared with other countries.

5. Demonstration project comparisons

Key points:

- A comparison of demonstration hydrogen production projects using electricity from existing nuclear power plants reveals a number of 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 laboratories and electrolyser companies.
- 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.

Utility strategy and climate targets

Many of the utilities forging forward with nuclear hydrogen demonstration projects have set their own decarbonization targets, as shown 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 elaboration of explicit policies by governments are a major encouragement for utilities to pursue nuclear hydrogen projects. For example, Canada and the UK include hydrogen from existing nuclear power in their national hydrogen strategies and are positioning nuclear power as one of the leading methods of hydrogen production. Nuclear hydrogen energy in the Russian Federation has also gained support at the state level, with a detailed action plan and concept officialized in decrees on 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

Table 2. Roadmap for low carbon electricity

	2020s	2030s	2040s	2050s
Energy Harbor	• Become a 100% carbon free, energy infrastructure and 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 electricity 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.	-	-	-
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.	-
Bruce Power	• Achieve net zero GHG emissions (both direct and indirect) by 2027.	-	-	-

Source: adapted from Ref. Energy Harbor (2022b); Xcel Energy (2022); APS (2020); Constellation Energy (2022a); EDF Energy (2021); Vattenfall (2021e); Bruce Power (2021).

cut carbon emissions by 80% before 2030 [Xcel Energy, 2022]. The utility has been changing its energy mix by incorporating wind and solar power, and retiring coal power plants, and it considers that with these economically available technologies, the interim target is achievable. On the other hand, the utility has underlined that looking beyond 2030, advanced carbon free, 24/7 power technologies at affordable prices will be needed to reduce the remaining 20% of carbon, and more innovation is required today. As one of these technologies, zero carbon fuels, such as hydrogen produced using nuclear energy, will be included in these ambitious goals.

APS reported on its clean energy commitment in 2020 to create a sustainable energy future for Arizona, with three goals: to reach "100% clean, carbon free electricity by 2050", to achieve "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 providing 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 holds the key to solving 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 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** also 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 and one is producing hydrogen with nuclear power generation — "utilize nuclear power generation to produce clean fuels and electrify industrial processes and transportation with an historic opportunity to contribute to a national hydrogen and clean fuels strategy". 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

Figure 31. Number of utilities engaging in cost reduction methods

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

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 would reduce the costs of hydrogen production. Assuming that nuclear plants can make money selling hydrogen, this new revenue stream is also one way of increasing revenues and keeping the plant online. Another approach to increasing 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 low temperature electrolysers by about 10–30%.

As shown in Fig. 31 on the previous page, five of the nine utilities surveyed are considering the utilization of surplus electricity, 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 the HTE in the place of the LTE.

Utilization of surplus electricity

Xcel Energy is considering the constant operation of an electrolyser in its demonstration project since it will account for only a small percentage of the nuclear plant's output. During the demonstration project, the intention is to operate the electrolyser using power from behind the meter at the NPP.

However, Xcel Energy has considered a different operating paradigm for a large scale system that would maximize NPP value. The paradigm would be 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 paradigm has the potential to maximize nuclear plant revenue and reduce overall system costs.

PNW Hydrogen and APS plan to run the electrolyser during off peak demand periods to produce hydrogen when wholesale market conditions reflect low priced electricity from solar energy. The company expects to run the demonstration project electrolyser for about 16 hours a day, since for about 8 hours a day electricity from the NPP will need to be 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 the company plans to operate 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 has announced its 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 installed capacity utilization rate [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 Power 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 will also use steam and electricity from a nuclear plant 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 150–200°C 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 is installed in future, 1.5 megawatt thermal (MWt) of steam will 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 180°C will be sufficient for solid oxide electrolysis and will contribute to increasing the efficiency of hydrogen production by around 10% [Nuclear Industry Association, 2021], with minimal disruption to nuclear reactor technology. The largest HTE to date is within the kW range, and so the challenge is to make them large enough for commercialization considering the rapid cell degradation.

Appropriate capacity and production

Electrolyser capacities are becoming larger and larger as a result of the expected cost reduction from economies of scale. However, the capacity of the electrolyser in nuclear hydrogen production projects remains smaller. As shown in Fig. 32, almost all utilities using the LTE start with a small scale hydrogen production 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 will demonstrate a 2 MW low temperature electrolyser to produce commercial quantities of hydrogen.

PNW Hydrogen and APS are considering the installation of a 17 MW PEM electrolyser in their demonstration project. The size of hydrogen production has 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 believe that the manufacturing of PEM electrolysers at scale will continue to drive the costs of electrolysers lower, while increasing the manufacturing capability and further enabling scale up.

Constellation Energy will install a 1.25 MW PEM electrolyser at the Nine Mile Point NPP. The company considers that the PEM technology is suitable for a small demonstration project. Potential scale-up technology is yet to be assessed. The NREL and Nel Hydrogen have completed a factory acceptance test for a prototype electrolyser.

Rosatom is actively developing low temperature electrolysis units of modular design based on the proprietary designed anion-exchange matrix. Using this technology, a test facility with a 1 MW electrolyser will initially be built, but the electrolyser capacity can eventually be increased to 10 MW. Electrolysers and other main process equipment manufactured by Rosatom will be used in the creation of the bench-scale test.

Bruce Power's feasibility study is exploring multiple options in terms of electrolyser technology, size and other options to scale. Bruce Power expects that its demonstration project will begin with roughly a 5 MW electrolyser, with the option to scale up to 20–100 MW in the medium term.

High temperature electrolysis

Xcel Energy plans 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 considers that it will need to increase the size of the HTSE in future, but it has no specific plans to do so at this time.

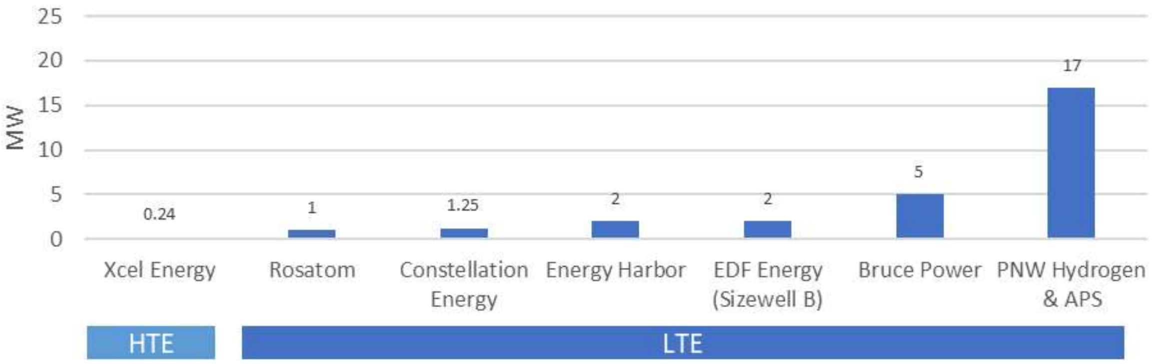
EDF Energy plans to install approximately a 2 MW alkaline or PEM electrolyser to produce around 800 kg of hydrogen for various vehicles through a demonstration project powered by the Sizewell B NPP. In this project, an HTE will also be installed at the Sizewell C NPP, but the electrolyser size remains to be determined.

Government support

The US and UK governments have provided funding support for demonstration projects to expand hydrogen supply capacity. The USA also provides funding for nuclear hydrogen projects with the perspective of expanding the use of nuclear energy.

Nuclear hydrogen demonstration projects owned by **Energy Harbor**, **Xcel Energy**, **PNW Hydrogen and APS**, and **Constellation Energy** in the USA; and **EDF Energy** in the UK have benefited from these funds.

Figure 32. The scale of electrolysers at the beginning of projects



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

Vattenfall's HYBRIT project was granted the equivalent of approximately $25 million in financial support from the Swedish Energy Agency to begin a study to scale up a demonstration project [Vattenfall, 2020b].

Bruce Power's nuclear hydrogen project has so far not received any financial support from the Canadian government. However, Canada has a carbon price, which will help to push the market towards low carbon solutions. Also, Canada's clean fuel standard, which includes a CAD $1.5 billion fund to incentivize zero emission fuels such as hydrogen, will likely help the nuclear hydrogen project.

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 companies; and (b) the milestone approach.

Collaborating with other companies 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, 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** and **PNW Hydrogen and APS** are cooperating in a consortium with the INL to receive technical support for hydrogen production. **Energy Harbor** and others have also launched the GLCH coalition with the goal of creating a hydrogen supply chain and job opportunities by using an NPP as a major hub for hydrogen production. The coalition includes, as major end users, Cleveland-Cliffs, which intends to use hydrogen for steelmaking; Toledo Rea Regional Transit Authority, which is proposing a project to operate hydrogen buses; and GE Aviation, which is considering 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]. Furthermore, **Xcel Energy** is collaborating with the ANL and the NREL, in addition to the INL, to complete a technoeconomic analysis of regional nuclear-to-hydrogen integration opportunities. In addition, it has been announced that multiple stakeholders in research, academia, industry and state level government will be cooperating in the **PNW Hydrogen and APS** project. Among these partners, OxEon, which is developing the SOEC, will be providing insight on the electrolyser. Siemens, which is developing gas turbines with hydrogen as fuel, and the Los Angeles Department of Water and Power, which is participating in another project to operate gas fired power plants with hydrogen, will be providing their input on the use of hydrogen in gas fired power plants [US DOE, 2021].

Constellation Energy is collaborating with Nel Hydrogen, the INL, the ANL and the NREL. The NREL and Nel Hydrogen are developing the PEM electrolyser, and the INL is developing 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.

Table 3. Collaboration with companies, laboratories and end users

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

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

EDF Energy collaborated with Lancaster University, the European Institute for Energy Research and Atkins consulting firm to conduct a feasibility study for hydrogen production at the Heysham NPP. Also, the company's Sizewell B and Sizewell C nuclear power stations 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. This hydrogen cluster project will be developed with Ryse Hydrogen, which is building a hydrogen production and distribution network. Also participating in the scheme are Wrightbus, a bus manufacturer, and JCB, which manufactures equipment for construction, agriculture, waste handling and demolition.

Vattenfall has created HYBRIT, a collaboration between the LKAB mining company and SSAB steel producer, supported by the Swedish Energy Agency. For this project, hydrogen will be used in the place of coal for steel production.

Bruce Power is involved in a feasibility study on the case for nuclear hydrogen production. The project, which explores the feasibility of using excess energy for hydrogen production, is proceeding in collaboration with the biofuels production company, Greenfield Global, as well as Hydrogen Optimized, which has the electrolysis system technology, and the agricultural co-operative Hensall Co-op.

Milestone approach

Constellation Energy has divided its hydrogen demonstration project into budget periods 1 and 2. Budget period 1 includes site selection and initial engineering design. In August 2021, the decision was made to proceed to budget period 2. In budget period 2, the developed electrolyser will be installed at the Nine Mile Point NPP, and demonstration tests will be conducted.

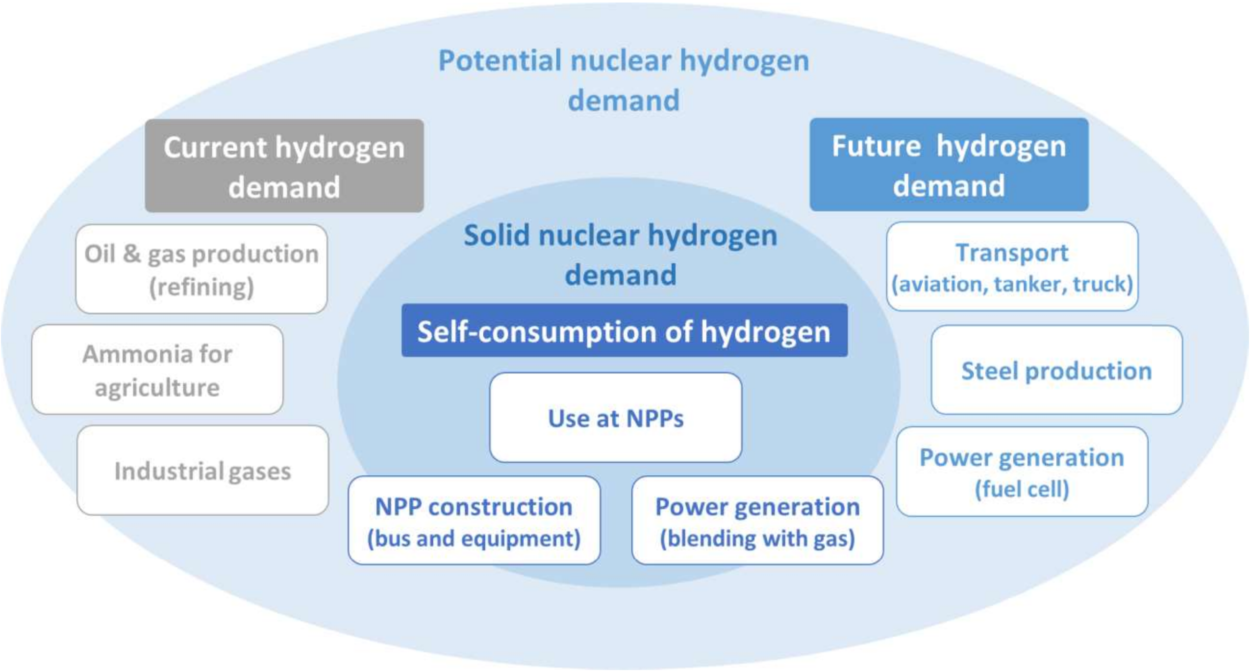
EDF Energy's Hydrogen to Heysham project was divided into a feasibility study during phase 1 and demonstration in phase 2. During phase 1, it was confirmed that the system was technically feasible, with compliance in relation to all of the relevant safety requirements. There was strong interest from local customers, but the hydrogen price was not competitive with that of gas or diesel inputs that were used at the time of evaluation. Given these commercial challenges, the project did not proceed to phase 2.

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 off take solutions. Many nuclear hydrogen projects are still in the demonstration stage, and the amount of hydrogen produced is small. As shown in Fig. 33, utilities are therefore implementing or planning to use hydrogen produced at NPPs for their own use,

Figure 33. Nuclear hydrogen demand development



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

such as to cool generators or add it to the primary cooling water so as to suppress the generation of oxygen due to radiolysis, and to prevent corrosion cracking of materials due to dissolved oxygen. If the owners of the hydrogen projects also own natural gas fired power plants, they may consider blending hydrogen with natural gas and using it as fuel, which is the most reliable demand. 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 future.

Energy Harbor is looking at a business model that would provide an alternative means of revenue outside of supplying power to the grid. There are many potential sources for hydrogen demand, including oil refineries, steel production and public transport in the area where the Davis-Besse NPP is located. The company is exploring current and project demand and has not specified the applications yet.

Xcel Energy is currently evaluating the best application for its hydrogen. In the demonstration project, Xcel Energy will not be able to produce a sellable quantity of hydrogen due to the small size of the project. As a result, the company is considering using the hydrogen from the demonstration project at its own NPPs. The BWR at the Monticello site requires much more hydrogen than the pressurized water reactor (PWR) at Prairie Island where the demonstration project will be conducted. However, the Monticello nuclear generating plant is 145 km away from the Prairie Island NPP, and so Xcel Energy is evaluating whether the cost to compress, store and ship the hydrogen can offset the savings from hydrogen produced on site.

After scaling up the project, the company's potential uses for hydrogen will include oil and gas production, agricultural ammonia manufacturing, and transport and power generation.

PNW Hydrogen and APS will blend 30% hydrogen with 70% natural gas, and will 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 have a more ambitious goal of co-firing up to 50% hydrogen without any mechanical changes to the plant, although there could be some complications related to air quality permits. PNW Hydrogen and APS have avoided regulatory issues with this demonstration project by selecting a site that is small enough to avoid having to obtain an environmental compatibility certificate.

Constellation Energy intends to supply its own NPPs 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 future hydrogen markets. The company is focusing on hydrogen demand as one of the determining factors for the demonstration project site, and has conducted a study of potential nuclear hydrogen demand in the future within 40 km of Constellation Energy's power plants. For example, Constellation Energy has 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 will 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 Sizewell 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 the industry, transport and energy sector, 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. In order 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 is also focusing on hydrogen production for export and is considering Europe and the Asia-Pacific region as strong potential markets.

Vattenfall began producing hydrogen at the Ringhals NPP to supply it with hydrogen. However, the utility 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 supply the surplus hydrogen to gas companies. It has already signed a contract with Linde Gas Aktiebolag, for instance.

Bruce Power has listed promising local markets for nuclear 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 Fig. 34, 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 nor 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 the APS natural gas power plant and Vattenfall's steel 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** are installing or planning to locate LTEs near NPPs, and there are several reasons for this. By locating the electrolyser close to the power plant, Energy Harbor is trying to lower the power cost to the electrolyser and the transmission cost so as to establish competitive pricing. Constellation Energy and EDF Energy are prioritizing the use of hydrogen at their own NPPs, and Energy Harbor will likely be its own customer as well. Rosatom is developing hydrogen compression or liquefaction systems and transport with an on-site hydrogen production demonstration project. OKG is also the original owner of the hydrogen production facility, and so it can use the hydrogen at its own NPP. For this reason, the facility is located near the NPP. The company plans to make maximum use of this facility and will also produce hydrogen for supply outside the NPP at the same hydrogen plant.

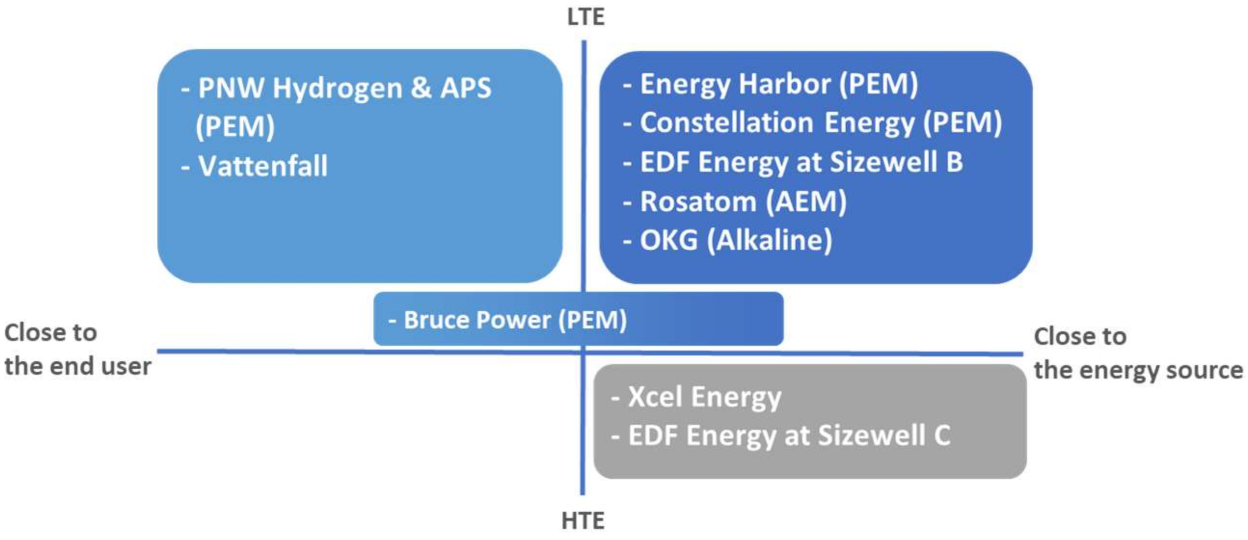
Xcel Energy and **EDF Energy** are also considering the installation of HTEs next to NPPs in order to minimize the distance needed to transport the steam. Xcel Energy is working through the regulatory process for its small scale demonstration project as it considers the plant modifications necessary for the HTE, which are more complex than those for the LTE due to routing steam and condensate lines for the HTSE system. The company 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 plan 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 will be using 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 steel and chemical plants, which have relatively high capacity demand and use electricity from the grid to produce hydrogen. A large hydrogen storage facility is also under construction next to the steel plant. Avoiding grid connection costs will be a challenge in future.

Figure 34. The type and location of the electrolyser



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

Multiple locations

For its demonstration project, **Bruce Power** is considering multiple locations, for example placing the electrolyser nearby the NPP or in a dedicated facility nearby the end users. Both on-site and off-site options are under consideration. However, the hydrogen that is produced can only be considered low carbon if it can be demonstrated that it was produced using electricity from the NPP.

Creating demand through clusters

To solve the problem of ensuring reliable hydrogen demand, several projects are underway to create hydrogen clusters. Several hydrogen cluster projects that include hydrogen production using existing NPPs have also been started. The demand for hydrogen in these clusters would thus be concentrated, and the infrastructure could be developed intensively.

EDF Energy is participating in the Freeport East Hydrogen Hub and will produce a large amount of hydrogen via nuclear energy at the Sizewell B NPP, and then at the Sizewell C NPP once it comes online. 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 in industrial processes, and transport to increase the use of electricity and hydrogen from nuclear power. Thus, the characteristics of this port cluster are the choice of nuclear power as the main hydrogen supply technology and stimulation of hydrogen demand in various types of transport. Another feature of this cluster is the ease with which offshore wind energy can be used to supplement electricity production.

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 needed. In addition, in order to keep the transport distance of hydrogen from the Russian Federation as short as possible, hydrogen production facilities in the Russian Federation tend to form clusters in regions close to Europe and Asia, where hydrogen imports are being considered.

6. Conclusions

Factors for deployment at present

In order for hydrogen produced from nuclear power to be deployed on a broader scale, it is important to make use of demonstration projects and their results to inform future projects. Similarities, differences and challenges should be examined to determine, for example, whether the attributes of one project should be shared among other projects or whether these attributes are specific to the unique goals and regional considerations of the demonstration projects in question. In the case of hydrogen demonstration projects, some similarities and differences have been observed, as shown in Fig. 35.

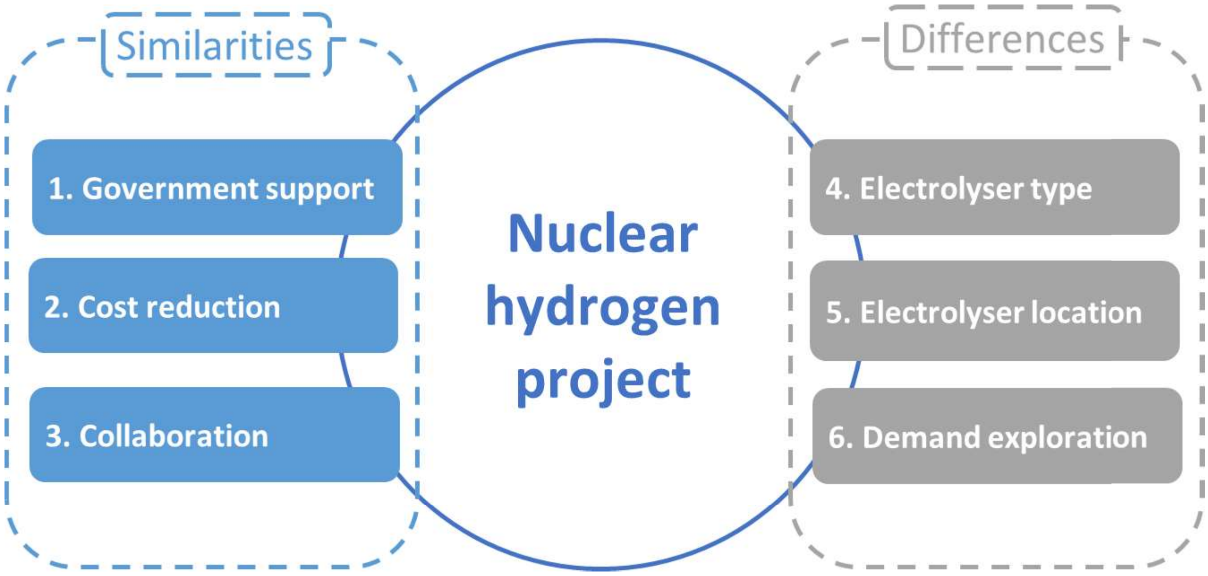
Some of the observed project similarities that could continue include:

- Government support in various forms has shown to be key to project promotion. Because existing nuclear power plant based hydrogen production projects are still not competitive with fossil fuel based hydrogen production, and it is not clear whether they will be profitable and sustainable in the future, it is not easy for utilities to invest significant amounts in these projects. 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, the inclusion of hydrogen production using existing nuclear power plants in national hydrogen strategies or hydrogen roadmaps provides additional support for utilities by increasing certainty in the future prospects of such projects.
- Pathways to obtaining cheap electricity for hydrogen production vary. In order to mitigate the cost of electricity, which makes up the majority of the total cost of hydrogen production, it is effective to produce hydrogen when electricity costs are low. For example, hydrogen production could take place during times of excess electricity supply from renewable energy or from nuclear power and during the night when electricity demand is low. Such solutions would avoid having to simply curtail nuclear power or sell electricity at lower prices.
- Various methods are being used to increase the probability of success and to reduce the cost and losses. Thus far, demonstration projects have remained small so as to keep costs relatively low. For many projects, the size of the electrolyser has been about 1 MW. 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 not been carried out independently, but in cooperation with research institutes, electrolyser manufacturers and companies with hydrogen demand.

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 used on a commercial scale, but each has

Figure 35. Factors related to current hydrogen project deployment



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

advantages and drawbacks, including capital expenditures, limitations on rapid output adjustments, efficiency, size and durability. While the LTE technology was chosen in many projects, some projects chose the high temperature electrolyser (HTE) technology to take advantage of the characteristics of nuclear power, which produces not only electricity but also heat. The HTE technology is expected to show some increases in efficiency as opposed 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 projects exist today. In addition, there are also regulatory issues specific to nuclear power, which concern installations that are next to a nuclear power plant (NPP).

- The location of the electrolyser can be either near the NPP or near the hydrogen demand facility — in which case it would use nuclear electricity through the grid. The production of hydrogen on-site is ideal when the hydrogen is mainly used by the NPP. When, on the other hand, the hydrogen is produced on-site, the challenge of transporting the hydrogen to the end use location remains an important factor. The choice 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. The choice of locating the electrolyser closer to the demand facility nonetheless comes with its own challenges, including grid interconnection and the associated costs, as well as certification issues related to producing hydrogen using electricity from NPPs. Both cases show the importance of considering not only the cost of hydrogen production, but also 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. Thus, while each project may target a different market and have different ways of finding or creating markets, all utilities nevertheless have in common the need to search for a reliable revenue stream as the most important aspect of their hydrogen project.

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

- A taxonomy has emerged that uses a colour scheme to indicate the source or process of hydrogen production [Bulletin H2, 2021]. While this taxonomy may be a useful reference for some users, it places too much emphasis on factors other than the carbon intensity of the hydrogen, which may ultimately exclude some low carbon technologies needed for hydrogen production. In order for the potential of hydrogen to gain widespread acceptance and deep penetration into worldwide and economy wide decarbonization efforts, objective, transparent, verifiable and harmonized methods are expected to be in place to measure hydrogen's carbon intensity.
- Hydrogen can serve both electric applications (e.g. an energy storage tool) and non-electric applications (e.g. transport 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 — depending on the application — be included in the hydrogen or electricity price. Once a market for hydrogen develops and hydrogen producers begin to switch back and forth between producing electricity and hydrogen, deregulated power assets are likely to include the opportunity cost of hydrogen in their electricity offers to ensure efficient operations.

  However, given the regulatory limitations, it is likely that hydrogen produced by regulated power assets will have to allocate the cost of the electrolyser to their customers, and therefore they will presumably be limited to selling the hydrogen solely for electric applications. In regulated power markets, the electricity price paid by customers is the sum of capital investments and other costs entailed by the regulated utility. For this reason, it is important to point out that utilities in the regulated electricity market may have to consider facilitating deregulation in order to use hydrogen for non-electric applications.

Future development and scheduling of the demonstration projects

Almost all nuclear hydrogen projects are still in the early stages of demonstration before hydrogen production has in fact begun, and these projects are only expected to be completed in several years. It will be useful to follow these projects closely in order to identify successes and challenges in the deployment of hydrogen production using electricity from NPPs. As nuclear hydrogen projects are scaled up to commercial size, it is important to identify how to resolve challenges that arise, such as scaling up the electrolyser, meeting regulatory requirements, transporting and storing hydrogen, further development of hydrogen demand, surveying the water supply and stakeholders and public engagement.

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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
BWR	boiling water reactor
CAPEX	capital expenditure(s)
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)
ENEC	Emirates Nuclear Energy Corporation
EPR	European pressurized water reactor
EPRI	Electric Power Research Institute (USA)
ETC	Energy Transitions Commission
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 Program (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)
IRENA	International Renewable Energy Agency
JAEA	Japan Atomic Energy Agency
kg	kilogram
kW	kilowatt
kW·h	kilowatt hour(s)
LCOE	levelized cost of energy
LHV	lower heating value
LKAB	Luossavaara-Kiirunavaara AB (Sweden)
LTE	low temperature electrolyser
LTO	long term operation
MW	megawatt
MWe	megawatt electric
MWt	megawatt thermal
MW·h	megawatt hour(s)
NE	Office of Nuclear Energy (USA)
NPP	nuclear power plant
NREL	National Renewable Energy Laboratory (USA)
O_2	oxygen
O&M	operations and maintenance

OKG	OKG Aktiebolag
OPEX	operational expenditure(s)
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	sulfur-iodine
SOEC	solid oxide electrolyser cell
SSAB	Svenskt Stål AB
TW·h	terawatt hour(s)
VVER	vodo voddyanoi enyergeticheskiy reaktor (water-water energetic reactor)

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