Nuclear Hydrogen Production

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Abstract

This project explores hydrogen production through nuclear energy, addressing the advantages and challenges of this emerging technology, divided into several sections that provide a global overview. Initially an introduction to the current context and the importance of hydrogen in the modern economy is presented. Next, the theoretical fundamentals of nuclear energy and the different methods of hydrogen production, such as conventional electrolysis (CE) and high-temperature steam electrolysis (HTSE) are explored, utilizing energy sources like nuclear reactors (APWR and HTGR), electricity from the grid, solar photovoltaic (PV) and wind. After, the economic analysis highlights the costs of hydrogen production and compares nuclear and renewable methods, showing that renewable sources have the lowest production costs but nuclear energy offers a large-scale solution to meet the growing energy demand. Subsequently, the future perspectives section explores the technical, economic and social challenges of implementing nuclear hydrogen production, including the high investments required and public acceptance. Finally, this project examines nuclear hydrogen demonstration projects in different countries, emphasizing that in present days commercial systems do not exist yet, but significant progress is being made in testing and pilot phases. With advancements in technology and regulatory support, it is expected that some of these projects will achieve commercial viability in the next decade.

1 Introduction

A future energy economy will need to replace oil and reduce greenhouse gas emissions (GHGs) for climate protection. Hydrogen has the potential to play a significant role in the world's transition to 100% clean energy. Like electricity, hydrogen is an energy carrier (but not a primary energy source), has some potential to replace oil as a transport fuel and in other applications. It can be used across multiple sectors to store and deliver usable energy to power the grid, drive industrial processes, or create energy-dense fuels needed for long-haul trucks and aeroplanes for example. [9]

According to The Global Hydrogen Review from 2024, the Global hydrogen demand reached 97 Mt in 2023, an increase of 2.5% compared to 2022. Demand remains concentrated in refining and the chemical sector, and is principally covered by hydrogen produced from unabated fossil fuels. As in previous years, low-emissions hydrogen played only a marginal role, with production of less than 1 Mt in 2023. However, low-emissions hydrogen production could reach 49 Mtpa by 2030 based on announced projects, almost 30% more than when the Global Hydrogen Review 2023 was released.[10]

Most hydrogen today is made by steam reforming of natural gas or coal gasification, both with carbon dioxide (CO2) emissions however the future demand will be mainly for zero-carbon hydrogen. Other plans for production are essentially based on electrolysis using electricity from intermittent renewable sources, this type of process faces challenges like inconsistent energy supply, lower efficiency, higher capital and storage costs, and technological limitations, making it less economically viable compared to the first described.[11]

Nuclear power is the second largest source of clean energy after hydropower. The energy to mine and refine the uranium that fuels nuclear power and manufacture the concrete and metal to build nuclear power plants is usually supplied by fossil fuels, resulting in CO2 emissions; however, nuclear plants do not emit any CO2 or air pollution as they operate. And despite their fossil fuel consumption, their carbon footprints are almost as low as those of renewable energy.

With this and given the necessity of hydrogen production from a source that is not so pollutant and that is not intermittent there are several nuclear projects around the world that are exploring the use of nuclear energy to produce hydrogen. Among other alternatives, using nuclear energy as the primary energy source for hydrogen production is advantageous for two main reasons. The first advantage is that nuclear reactors do not emit any greenhouse gases (GHG), the most important being CO2. The second advantage is that nuclear energy can contribute to large-scale hydrogen production, which is necessary given the fast increase in hydrogen demand. Other relevant aspect is a nuclear based energy supply is eliminating supply uncertainty and the sensitivity of energy prices to the volatility of natural gas and other fuel prices.

In this work we are going to explore the various ways of producing hydrogen through nuclear energy sources, the main challenges that these methods face, the economic viability of possible projects and perspectives in the future.

2 Theoretical Fundamentals

2.1 Nuclear Energy

Nuclear energy is a form of energy released from the nucleus, the core of atoms, made up of protons and neutrons. This source of energy can be produced in two ways: fission – when nuclei of atoms split into several parts – or fusion – when nuclei fuse together. [12]

Nowadays to produce electricity is through nuclear fission, the technology to generate electricity from fusion is still in research and development. Uranium fission starts with the absorption of a slow-moving neutron by the non-stable isotope U-235. The obtained U-236 splits into Ba-139 and Kr 94 and releases three free neutrons. The mass defect of about 0.2 u (unitary atomic mass units) is converted into an energy of about 200 MeV (figure at right). We have u 1.66×1027 kg, and the atomic energy unit electron volt, eV, is about 1.60×1019J. Nuclear fusion is the process of combining light atomic nuclei, like deuterium or tritium, under extreme heat and pressure to form a heavier nucleus and release massive energy. The fusion of a deuterium and a tritium nucleus creates an alpha particle, a neutron and 17.6 MeV energy. The latter should sustain the plasma to reaction temperature, so that escaping neutrons, which absorb 80% of the fusion energy, heat the water which drives the steam turbines. It's not used today due to the fact that at the end of the last century, it was found that turbulent processes in plasma give rise to energy and particle losses and reduce the energy confinement time in which plasma can be kept stable. But it is expected that in the future it will be a process used. [13]

So nuclear plants, are composed of nuclear reactors and their equipment produces and controls the release of energy from splitting the atoms of certain elements, causing chain reactions, normally fuelled by uranium-235, releasing energy that is used as heat to make steam that generates electricity, this is called fission. The steam is then channelled to spin turbines, activating an electric generator to create low-carbon electricity. A nuclear reactor needs to have, fuel uranium, a moderator, control blades, a coolant, a pressure vessel, a steam generator and a containment. The primary design used is the pressurized water reactor (PWR), where water is maintained at temperatures exceeding 300°C under high pressure within the primary cooling and heat transfer system, producing steam in a separate secondary loop. But there are many types of reactors, that work differently according to the final goal because they are optimized for specific purposes, fuels, and safety requirements.

Nuclear power generation has existed since the 1960s but saw massive growth globally in the 1970s, 1980s, and 1990s. Following fast growth during the 1970s to 1990s, global generation has slowed significantly.[1] But we also see that production has once again increased in recent years. It's important to recognize that economic base-load production of electricity makes nuclear energy competitive with fossil-fuelled power plants, with the comparatively low fuel cost helping to stabilize the price of electricity within the energy mix, and is an energy source with no GHG emissions so contributes to 'sustainable' development.[14]

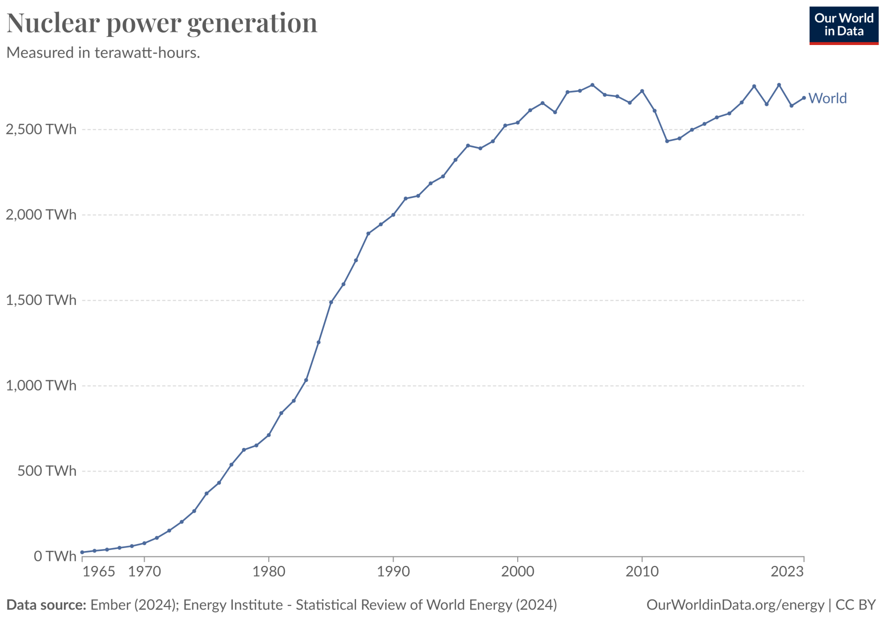

Figure 1: Nuclear power generation in the world [1]

The nuclear industry must maintain and improve the safety and reliability of existing plants while also developing innovative next-generation nuclear technologies to address public safety concerns. Studies demonstrate the potential for socially acceptable, environmentally friendly, and cost-effective nuclear solutions. This will ensure the continued viability of nuclear power in the long term.

2.2 Hydrogen Production

Hydrogen is the most abundant element in nature; however, it is not found in its natural and elemental form - it is obtained through compounds in which it is present. There are several technologies and various processes for obtaining it, which will be described in this section [15]. When it comes to hydrogen production, there are several different methods for generating this element. To facilitate the identification of the origin of hydrogen, a system of nuclei codes was developed. The most common colours include green, blue, grey and turquoise, but the choice of other colours may vary depending on the author. Although this nucleus system is widely used in scientific literature, it is not yet fully adopted by everyone. Table 1 presents an overview of the different cores associated with these production methods [2].

Color	Source of Energy	Source of Hydrogen	Production Process	CO_2 Emissions
Green	Renewable Energy	Water	Electrolysis	No direct carbon emissions
Gray	Non-renewable Energy	Natural Gas	Steam Methane Reforming	High
Blue	Non-renewable Energy	Natural Gas/Biomass	Steam Methane Reforming with CO_2 capture	Low to none - Carbon is captured after production
Pink	Nuclear Energy	Water	Electrolysis	No direct carbon emissions
Turquoise	Non-renewable Energy	Natural Gas	Pyrolysis	No direct carbon emissions
Black	Non-renewable Energy	Bituminous Coal	Gasification	High
Brown	Non-renewable Energy	Lignite Coal/Biomass	Gasification	High
Orange	Mix of electricity grid	Water	Electrolysis	Depends on the electricity mix
Red	Nuclear Energy	Water	Thermolysis/ Thermochemical process	No direct carbon emissions
Yellow	Solar	Water	Thermolysis/ Thermochemical process	No direct carbon emissions

Figure 2: Different Colors of Hydrogen [2]

The table 2 does not include white hydrogen, which refers to naturally pure hydrogen. The main focus of this work is the pink hydrogen, obtained from nuclear sources, which will be explored in the next chapters. The main purpose of this classification (colours) is to facilitate comparisons between different production methods. There are main categories in which colours differ, such as their environmental impact, the current distribution of hydrogen production methods, the costs involved in each process and the distance between hydrogen production and consumption. Environmental impact has been one of the most debated topics recently, especially by the scientific and academic community, since hydrogen production mainly aims to decarbonize fuels. To assess the global impact of each color, CO_2 emissions are essential. The energy sources used during production also influence carbon emissions. Processes that involve water, such as green and pink hydrogen, have low emissions, while processes that use fossil fuels have considerable emissions. These sources also affect production costs. As we see an increase in the price of fossil fuels, the cost of hydrogen produced in this way also increases. The distance between production and consumption locations must also be considered, since the shorter the distance, the lower the transportation costs. Currently, several countries have their own national hydrogen plans, as illustrated in Figure 3.

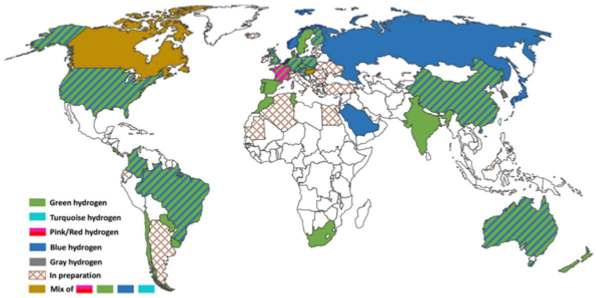

Figure 3: Colors of Hydrogen for the national plans of production of countries around the world [2]

The decision on which type of hydrogen to produce has been influenced by several factors across countries, such as the availability of natural resources, environmental impact, existing infrastructure and economic feasibility. It is worth noting that not all European Union countries plan to produce hydrogen exclusively from renewable sources. Many of them opt for a combination of green and blue hydrogen, while others, like France, consider a mix of pink and green hydrogen (explained in this specific case by their reliance on nuclear energy). As previously mentioned, research is underway into various technologies aimed at producing hydrogen in an economically viable and environmentally sustainable way, intending to avoid dependence on a single energy source. Some of the most common hydrogen-obtaining technologies include [15]:

Natural Gas Vapor Reforming: In this process, natural gas is heated to high temperatures in contact with steam, resulting in the production of hydrogen, carbon monoxide and carbon dioxide. Subsequently, the carbon monoxide is converted into additional hydrogen and carbon dioxide through a reaction with steam. The hydrogen yield is approximately between 70% and 90%, which is the predominant method of hydrogen production.

Electrolysis: In this process, electricity is used to separate water into gaseous hydrogen and oxygen. Renewable energy sources, such as solar panels, and nuclear energy can be used to generate this electricity, thus allowing for more sustainable hydrogen production, with no carbon emissions.

Gasification and Pyrolysis of Biomass: Hydrogen can be generated from high-temperature gasification and low-temperature pyrolysis of biomass such as wood chips, forestry debris, and domestic and agricultural waste.

Photobiological Process: Some photosynthetic microorganisms can produce hydrogen as part of their metabolic activities, using light energy.

Photoelectrolysis: In this process, sunlight is absorbed by a semiconductor material, splitting water into hydrogen and oxygen.

Pyrolysis: This method involves the decomposition of hydrocarbons without contact with water or oxygen, resulting in the formation of hydrogen and carbon. It can be applied to a wide range of organic materials and has diverse applications, from the production of hydrocarbons to obtaining carbon nanotubes and spheres [16].

As described above, nuclear hydrogen can be obtained through electrolysis. When a direct current is applied directly to an aqueous solution containing electrolytes (such as sulfuric acid, sodium hydroxide or potassium hydroxide), hydrogen is produced by the ionization of strong electrolytes dissolved in water. This hydrogen is called green if the current is provided by renewable energy, or pink if it comes from a nuclear source. The chemical reaction that describes this process, can be seen in expression 1 [17].

$$H_2O + \text{Electricity}\,(237.2\,\text{KJ/mol}) + \text{Heat}\,(48.6\,\text{KJ/mol}) \longrightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

This reaction happens in a device called an electrolyzer that can be composed of different materials depending on its type. Solid Oxide Electrolysers are a type of high-temperature electrolyser. They use heated water vapour that enters through the cathode side. An applied current causes the molecule to break and produce hydrogen and oxygen ions. The hydrogen protons are then united and the oxygen ions migrate through the electrolyte to the anode where they form oxygen molecules. Figure 4 represents the process described [3].

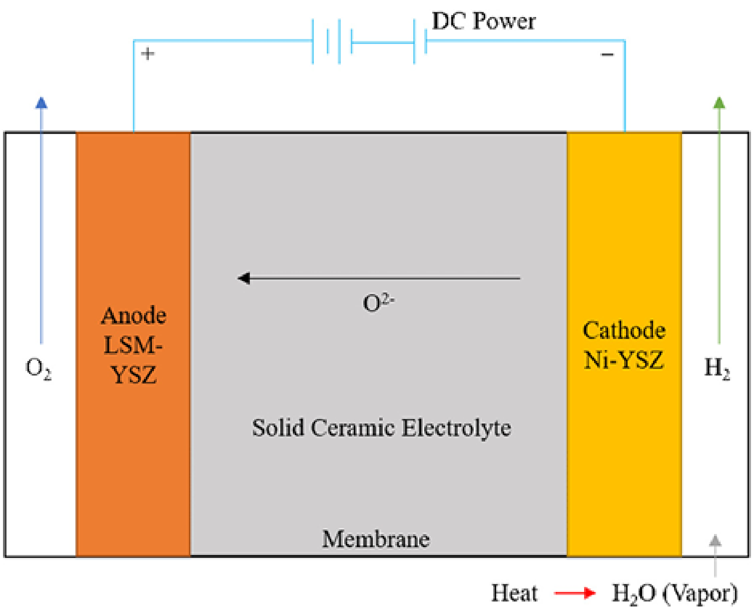

Figure 4: Solid Oxide Electrolyser scheme [3]

This method is capable of achieving an efficiency of around 75.85%, with hydrogen obtained at a purity of up to 99%. Such results reflect that it is a positive method. However, the downside is that it requires a high amount of energy for electrolysis, approximately 4.5-5.5 kWh to produce 1 cubic meter of hydrogen. That's why it is an advantage if we use a nuclear source [17].

3 Nuclear Energy Applied to the Production of Hydrogen

3.1 Production Methods

Nuclear Energy and Hydrogen are two important solutions for the urgent energy transition. The first is due to its capability of producing huge amounts of clean energy, the second is because it is able to store this energy and transport it elsewhere for usage. With high system level thinking, these two powerful vectors can be combined to create a complete, high performance and reliable method of producing and storing energy at large scale [6].

There are two main ways of producing hydrogen from nuclear energy. The first way uses the conventional process of green hydrogen, which is electrolysis, but instead of using electricity from renewable energy, it uses electricity from nuclear power production and the excess heat produced by the nuclear reactor. Thermochemical processes take advantage of the heat produced in the nuclear plant to drive chemical reactions.

Figure 5 represents the difference between these three methods. On one extreme we have pure electrochemical methods, that use electric current to trigger their reactions, on the other end we have pure thermochemical reactions that use both heat and electric energy for their reactions. [4]. In the right end of the temperature axis, there is the thermolysis process which is characterized by a one-step direct thermal decomposition of water that requires temperatures above 2500ºC [6]. This process is usually not used due to the temperature requirements and for the temperature to decrease, thermochemical cycles are used in replacement.

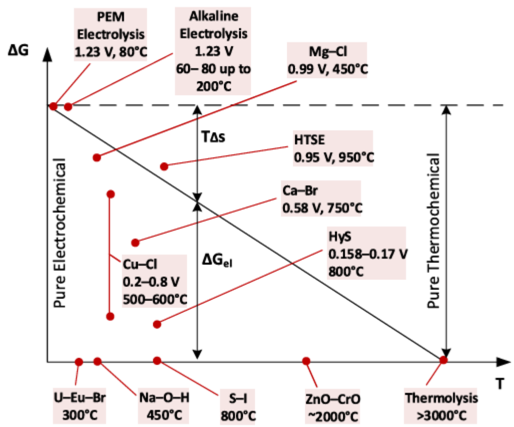

Figure 5: Temperature and theoretical electric energy required for different methods of producing hydrogen [4]

3.1.1 Electrolysis

In **High Temperature Electrolysis (HTE)**, there are multiple electrolysers technologies that can be used. For producing hydrogen with nuclear power, the one that is most advantageous and brings higher efficiencies is the Solid Oxide Electrolyser (SOE). This type of electrolyser is known for its high temperature of operation and integration of heat for combined heat and power. A scheme of a high-temperature electrolysis plant can be seen in Figure 6. In this type of nuclear production of hydrogen, both heat and electricity produced by the nuclear reactor are used, one to heat the water and the other to provide the electrical current needed [5].

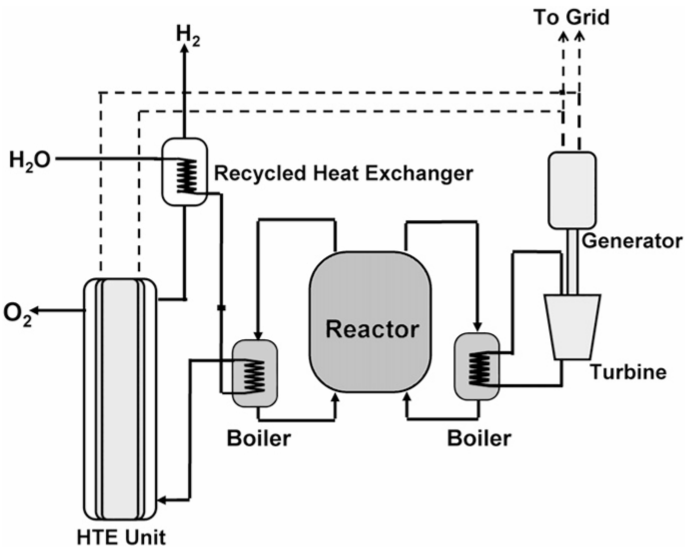

Figure 6: Scheme of a High-Temperature Electrolysis Plant coupled with nuclear reactor [5]

Hydrogen Production efficiency is given by the ratio between the High Heating Value of Hydrogen (HHV) and the sum of both electrical energy input and thermal energy input needed to produce the same amount of hydrogen as to HHV. For this process, a gas-cooled reactor was selected as the most appropriate and the plant can be seen of Figure 7. In this representation, we can see that the reactor is connected to an intermediate Heat Exchanger (IHX) and then to two Process Heat Exhangers (PHX) that heat the gas to the electrolysis temperature of 800ºC. In this plant, there is recirculation of H**2** for the reductive conditions of the cathode to be maintained [5].

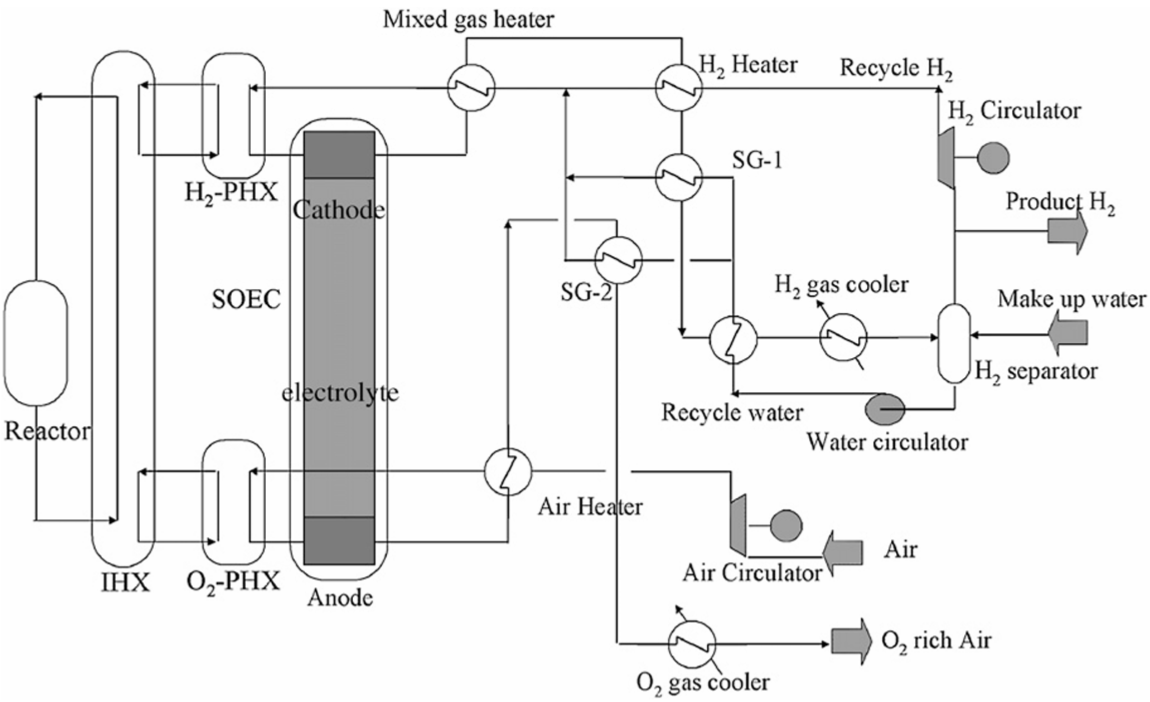

Figure 7: Plant system of Water electrolysis coupled with high-temperature gas cooled reactor [5]

The efficiency of producing hydrogen through this method, at an operational temperature of 800ºC, is of 53%, which corresponded to 130NL/h using 15 tubular solid oxide cells [5]. It is possible to achieve an electricity to hydrogen efficiency of up to 99%, but the electrode materials still need some further improvements to handle high temperatures for longer periods of time [6].

Low temperature Electrolysis (LTE) is compatible with all current operating nuclear reactors. The operational temperature is usually around 90 to 210 ºC and instead of using both heat and electricity produced by the reactor, LTE only uses the electricity, which makes the efficiency of the electrolysis process to be lower than that of HTE. LTE can be conducted with Alkaline Water Electrolysers (AWE) or Proton Exchange Membranes Electrolysers (PEME). The difference between the two consists on the type of materials that are used and the conductive ion of the reaction. The AWE are also more mature and more established commercially. Figure 8 shows a standard low-temperature alkaline electrolyser [6].

The Alkaline Water Electrolyser requires 4.7kWh to generate 1Nm^3 of hydrogen. Hydroxide ions act as a charge carrier between both electrocatalysts and through the membrane. The advantage of this process being on an alkaline medium is to avoid a corrosive environment. Multiple cells are assembled in series to increase capacity and lower leakage current [8].

Figure 8: Standard low temperature alkaline electrolyser [6]

3.1.2 Thermochemical processes

Thermochemical production of hydrogen can use multiple thermochemical cycles. They all require heat input which can jeopardize the safety of the process and therefore increase the challenges such as material compatibility and duration of the operation to not damage the equipment involved. It is possible to reduce the temperature required with the integration of electrical energy, thereby reducing challenges [4]. No cycle has been implemented on a commercial state, however, they all have been proven to be feasible and only have some design challenges [6].

The **Sulfur-Iodine (S-I) cycle** is one of the main thermochemical cycles for hydrogen production with nuclear energy. Figure 9 shows the three reactions that occur in this cycle. Firstly there's the decomposition of sulfuric acid at 800-850ºC. Then the Bunsen reaction, also known as hydrolysis that happens at around 120ºC. Finally, there is the decomposition of hydrogen iodide at 300-450ºC, producing hydrogen [4]. This cycle is one of the cycles that can achieve higher efficiencies, of up to 51% [6].

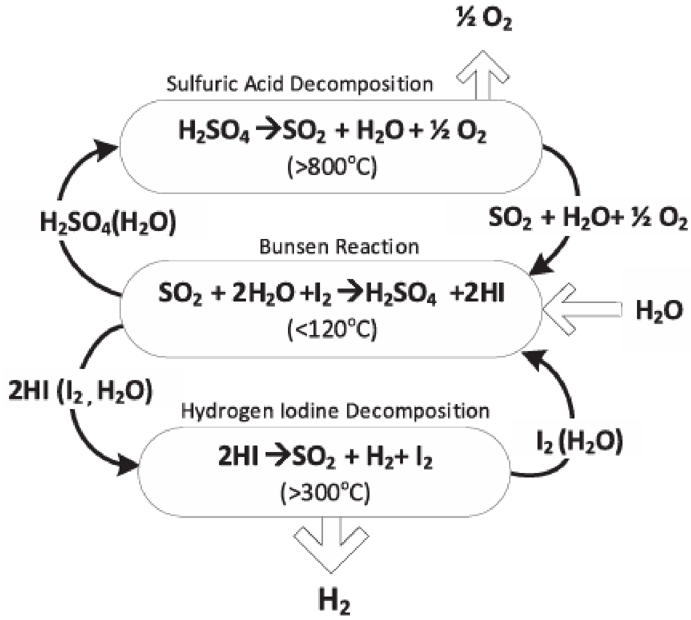

Figure 9: Sulfur-Iodine Cycle [4]

The S-I cycles are adaptable for large scale production of hydrogen with high efficiency and the cost is competitive with other technologies. Nevertheless, there are still some challenges regarding chemical kinetics and thermodynamics uncertainties that still need to be developed. Iodine supply around the world for iodine is also a target of concern for large scale implementation [4].

The **Hybrid Sulfur (HyS) cycle**, also known as the Westinghouse cycle, is a hybrid cycle that includes an electrochemical step along with the thermochemical decomposition of sulfuric acid. Both steps can be seen in Figure 10. The first step involves once again sulfuric acid decomposition at high temperatures. The electrochemical step is the sulfur dioxide depolarized, at a temperature of 80 to 120ºC[4].

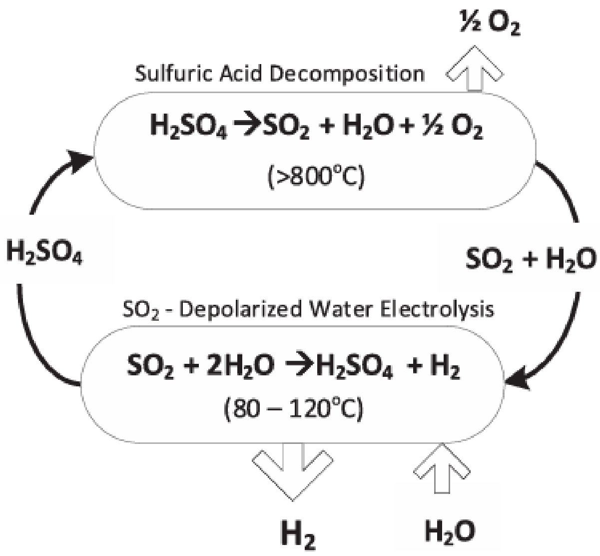

Figure 10: Hybrid Sulfur Cycle [4]

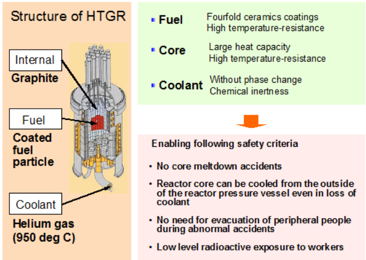

Figure 11: Structure of a HTGR

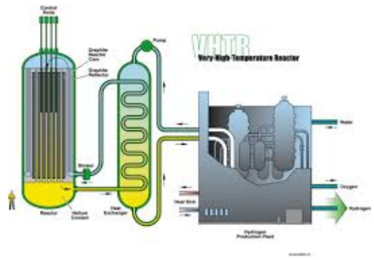

Figure 12: HTGR reactors connected to an

The great advantage of this process comparing with conventional water electrolysis is that is uses less than one third of the electric power required for it. The HyS cycle still require some improvements in order to be commercially available, involving advances in electrocatalyst materials and long term stability during operation [4].

3.2 Common Reactors

3.2.1 High-Temperature Gas-Cooled Reactors

High-temperature gas-cooled Reactors (HTGRs) are a type of nuclear reactor designed to produce both electricity and high-temperature process heat. This versatility is due to their ability to operate at extremely high temperatures, reaching up to 950°C. This makes them highly efficient and suitable for a wide range of applications beyond traditional electricity generation, including hydrogen production and industrial heating.

This nuclear reactor uses helium gas for its coolant, ceramic materials, mainly graphite, for its core structure, and able to supply nuclear heat outside. Also can produce high-temperature heat around 1000 degrees Celsius using ceramic materials which offer resistance to high temperatures and apply a gas turbine system which can achieve a high power generation efficiency of more than 45%. Fuel of the HTGR has a fourfold ceramic coating and it confines fission products even at a temperature of 1600 deg C. Since its core structure mainly consists of graphite which has enormous heat capacity, core temperature variation is very slow during abnormal accidents. Even during the loss of the helium gas coolant initiated by piping rupture events, the heat produced by the core will be removed by heat dissipation from the reactor pressure vessel so that the fuel will not fail. This means that the HTGR has significant safety which has no concern of core meltdown or radioactivity release accidents.

So HTGRs work by using helium coolant and graphite moderation to sustain nuclear fission in a safe, high-temperature environment. The helium coolant absorbs the heat from the fission process and is then used directly in gas turbines or indirectly to produce steam for power generation and industrial applications.[18]

3.2.2 Advanced Pressurized Water Reactor

The APWR is a four-loop PWR designed collaboratively by Mitsubishi Heavy Industries (MHI) and Westinghouse that uses a combination of active and passive safety mechanisms. The high-capacity APWR, with 1534 MWe (1700 MWe in Europe and the US), takes advantage of economies of scale and uses high-performance steam generators and low-pressure turbines with very large last-stage blades. The APWR allows operation with long fuel cycles, and increased flexibility such as the use of low-enriched fuel in order to reduce uranium requirements, the use of MOX cores and high burn-up fuels. [19]

4 Economic Comparison

4.1 Introduction to the Costs in Nuclear Hydrogen Production

Nuclear hydrogen production involves several key cost factors that must be considered to assess its economic feasibility compared to other production methods. These costs can be broken down into CAPEX (Capital Expenditure) and OPEX (Operational Expenditure), covering everything from the initial investment in nuclear infrastructure to ongoing operational and maintenance costs:

CAPEX (Capital Expenditure):

1. Nuclear Reactor Construction: The construction of a nuclear reactor, especially advanced generation reactors, involves high upfront costs. This includes building the reactor, obtaining licenses, and installing complementary systems such as high-temperature electrolysis units for hydrogen production.

2. Hydrogen Production Systems: Depending on the method used (high-temperature electrolysis, thermochemical processes), specialized equipment is required, adding significantly to the capital costs.

OPEX (Operational Expenditure):

1. Fuel Costs: Nuclear fuel (uranium or plutonium) is relatively cheap compared to fossil fuels but still represents a portion of the operational costs.

2. Maintenance and Reactor Operation: Nuclear reactors require regular maintenance, safety inspections, and periodic updates, adding to operational expenses.

3. Waste Management: The treatment and long-term storage of nuclear waste are significant economic and environmental considerations, contributing to ongoing operational costs.

4.2 Tools for economic analysis

When evaluating the economic feasibility of nuclear hydrogen production, some tools have been developed to provide detailed cost analysis, each designed to address different aspects of production technologies. These tools allow for precise modelling of the costs associated with various hydrogen production methods, enabling comparisons and optimization.

The table 1 shows some tools that can be used to perform the cost analysis:

These tools complement each other by addressing various aspects of hydrogen production, from nuclear-specific scenarios to broader hybrid energy systems.

4.3 Hydrogen Economic Evaluation Program (HEEP) Overview

The HEEP (Hydrogen Economic Evaluation Program) was developed by the International Atomic Energy Agency (IAEA) to conduct economic assessments of nuclear hydrogen production.

Tool	Description
HEEP	Evaluates the economic feasibility of hydrogen production using nuclear energy.
HydCalc	Models cost and technical feasibility, including hybrid systems combining nuclear and renewables.
G4-ECONS	Assesses the economic performance of Gen IV reactors, including hydrogen co-production.
MESSAGE	Integrated energy system planning tool, optimizing co-production of hydrogen and electricity.

Table 1: Summary of Tools for Hydrogen Production Economic Evaluation

The program consists of three modules: the pre-processing module, which allows the user to input data; the executing module, which computes the cost of hydrogen from the given input data; and the post-processing module, which shows the output after the execution.

In the pre-processing stage, we can divide the parameters into different categories as shown in Figure 13

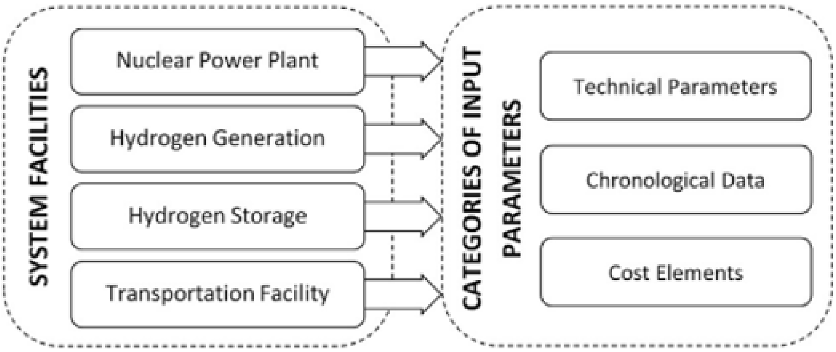

Figure 13: Categories of input parameters[7]

The list of technical parameters required for the HEEP modules is represented in Figure 14 while the cost elements of the modules is in Figure 15.

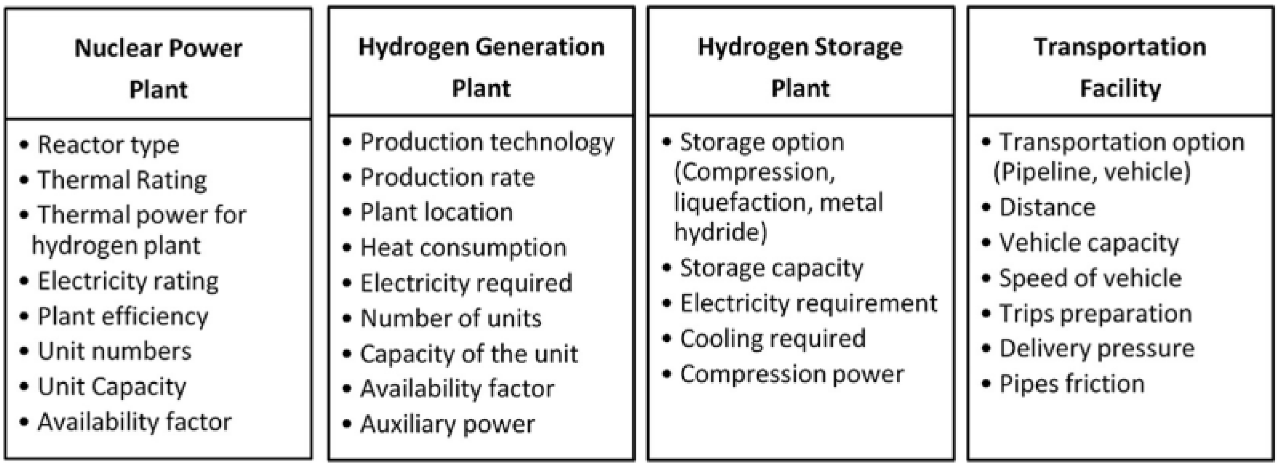

Figure 14: Technical input parameters[7]

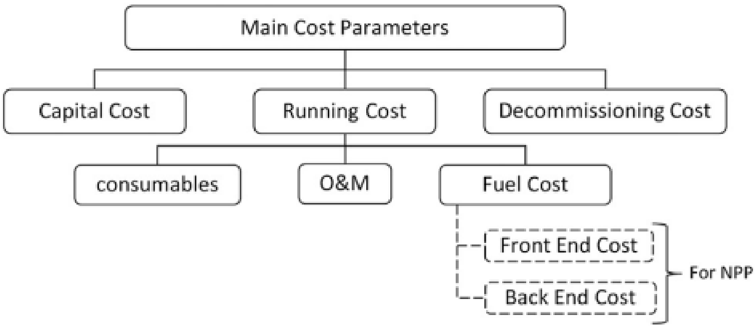

Figure 15: Main cost parameters[7]

These are the inputs needed to get to the Levelized Cost of Hydrogen (LCOH): This is a key metric provided by HEEP, showing the cost per kilogram of hydrogen produced. It allows comparison with other hydrogen production technologies.

The levelized cost of hydrogen (C_{H_2}) is calculated using the formula:

$$C_{H_2} = \frac{E_{NPP}(t_0) + E_{H_2,GP}(t_0) + E_{H_2,T}(t_0)}{G_{H_2}(t_0)} [8]$$

where: E_{NPP} is the cost of the nuclear power plant, $E_{H_2,GP}$ refers to the cost of hydrogen production and storage, $E_{H_2,T}$ refers to the cost of hydrogen distribution and $G_{H_2}(t_0)$ is the hydrogen output at the initial time t_0.

The total cost $E(t_0)$ is calculated as:

$$E(t_0) = \sum_{i=t_0}^{t_f} \frac{CI_i(t_0)}{(1+r)^{t_i-t_0}} + \sum_{i=t_0}^{t_f} \frac{R_t}{(1+r)^{t_i-t_0}} + \sum_{i=t_0}^{t_f} \frac{DC_i}{(1+r)^{t_i-t_0}} [8]$$

where: CI_i is the capital investment, R_t are the running expenses, DC_i are the decommissioning expenses and r is the real discount rate.

The hydrogen production cost $G_{H_2}(t_0)$ is calculated as:

$$G_{H_2}(t_0) = \sum_{t=START}^{t=END} \frac{G_{H_2}(t)}{(1+r)^{t-t_0}} [8]$$

where $G_{H_2}(t)$ is the hydrogen production in a selected year.

4.4 Methodology

To demonstrate how this economic analysis can be conducted, a study/paper that shows the use of HEEP tool was selected since HEEP offers comprehensive data for the different nuclear power plants, hydrogen production processes, and various storage and transportation options (though it can also be used for other energy sources).

4.4.1 Objective

The objective is to examine the impact of production scale on the cost of nuclear hydrogen production, considering four cases and to compare nuclear hydrogen production with non-nuclear options such as solar, wind, and grid electricity. All are based on the local electricity rates in the Kingdom of Saudi Arabia (KSA).

4.5 System description

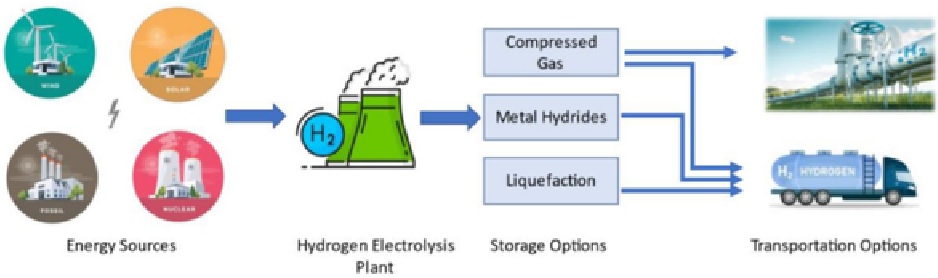

Figure 16: The layout of the hydrogen production, storage and transportation system [8]

The Figure 16 represents different case studies examining and comparing two energy sources. These energy sources are primarily two nuclear reactors: Advanced Pressurized Water Reactor (APWR) and High Temperature Gas-cooled Reactor (HTGR), representing two different reactor categories. For the water electrolysis process, two electrolysis technologies are considered: low temperature and high temperature electrolyzers. These electrolyzers are responsible for converting energy, i.e., electricity and/or heat to hydrogen. In the storage stage, three options are examined: CG to 20 MPa, MH, and LQ. Moreover, the cost of transportation to 500 km through vehicle and pipelines are estimated.

4.5.1 Storage

Compressed Gas

Hydrogen gas takes up a lot of space, so one common method for storage is to compress it to very high pressures, which makes it easier to store and transport. Currently, hydrogen can be stored in cylinders as compressed gas at pressures up to 700 bar. However, the higher the pressure, the more energy is required for compression, which increases the overall storage cost. For instance, to compress hydrogen from 20 bar (the pressure at production facilities) to 350 bar, it requires about 1.05 kWh per kilogram of hydrogen. This is the theoretical minimum energy needed, meaning that in practice, the actual energy used will be even higher. Figure 17 shows the required pressure for various applications.

Application	Pressure (MPa)
Pipeline transportation	3–8
Compressed underground storage	2–18
Ammonia synthesis	20–30
Fuel cells, hydrogen vehicles	35–70

Figure 17: The required pressure range for some applications [8]

Liquid

Liquefaction involves cooling hydrogen until it becomes a liquid, which increases its density and allows for more efficient storage. Because hydrogen has an extremely low boiling point, this process requires special cryogenic systems that use compressors to cool it down. One of the challenges of storing liquid hydrogen is preventing losses from boil-off, where heat entering the system causes some of the liquid to evaporate. To manage this, spherical or cylindrical tanks are often used, designed to minimize heat transfer and reduce evaporation. Liquefaction is energy-intensive. In theory, it requires about 3.3 to 3.9 kWh of energy per kilogram of hydrogen, but in practice, the actual energy needed is usually about three times higher.

Metal hydride

Many metals and alloys can absorb and release hydrogen in a reversible way. Hydrogen gas can be stored in these materials through two processes: adsorption and absorption. In adsorption, hydrogen atoms attach to the material's surface, whereas in absorption, the hydrogen atoms penetrate the material's internal structure, fitting into spaces within its atomic lattice. When the hydrogen is released (desorption), the atoms combine to form molecular hydrogen again. This method of storage is considered safer compared to liquid or compressed hydrogen storage. However, one drawback is that hydrogen storage in metal hydrides leads to heavier systems, making it less practical for transport purposes.

4.5.2 Transportation

Pipelines

Many experts consider pipelines to be the most energy-efficient way to transport hydrogen. However, building the necessary pipeline infrastructure involves high upfront costs, which need to be addressed. To counteract the energy losses caused by friction in the pipes during transportation, compressors are used throughout the pipeline network. Another issue with hydrogen pipelines is that hydrogen can seep through materials more easily than natural gas, leading to higher leakage rates. This results in greater maintenance costs compared to natural gas pipelines.

Vehicular

Until a comprehensive hydrogen pipeline network is developed, road transportation might be the preferred option. However, because gaseous hydrogen has a low energy density, transporting it by road requires a lot of energy, though it can still be done using trailers. Liquefied hydrogen, with its higher energy density, is more efficient and thus better suited for road transport. On the other hand, using metal hydrides for transport is less favorable because of their heavy weight.

4.6 Analysis

Like stated in the objectives of this section, this analysis has two main focuses. The first is to assess the impact of production scale on the cost of nuclear hydrogen production While the second is to compare nuclear hydrogen production with non-nuclear options.

4.6.1 Impact of scale on the cost of hydrogen

As explained before, this study focuses on the economics of electrolysis-based nuclear hydrogen production.

The four cases are developed for nuclear hydrogen production economic analysis at different scales. These four cases are presented in Figure 18.

Parameter	Case 1	Case 2	Case 3	Case 4
NPP	APWR1117	APWR360	APWR720	HTGR510
Thermal rating (MWth/unit)	3385	1089	2178	510
Heat for H2 plant (MWth/unit)	0	0	0	510
Electricity rating (MWe/unit)	1117.05	359.48	718.96	0
Number of units	2	2	2	2
Initial fuel load (kg/unit)	75,000	27,000	54,000	14,000
Annual fuel feed (kg/unit)	25,000	9000	18,000	5000
Overnight Capital cost (USD/unit)	5.96E+09	3.16E+09	4.66E+09	4.02E+08
Capital cost fraction- electricity generating infrastructure (%)	10	10	10	0
Fuel cost (USD/kg)	1.26E+03	1.85E+03	1.37E+03	3.66E+03
O&M cost (% of capital cost)	1.7	1.66	1.67	5.8
Decommissioning cost (% of capital cost)	2.8	2.8	2.8	11.7
H_2 Production Plant				
H_2 Production Plant	CE12	CE04	CE08	HTSE04
H_2 generation per unit (kg/yr)	3.92E+08	1.26E+08	2.52E+08	1.26E+08
Heat consumption (MWth/unit)	0	0	0	1020
Electricity required (MWe/unit)	2234	719	1438	0
Number of units	1	1	1	1
Overnight Capital cost (USD/unit)	1.31E+09	4.23E+08	8.45E+08	4.59E+08
Energy usage cost (USD)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Other O&M cost (% of capital cost)	4	4	4	17.23
Decommissioning cost (% of capital cost)	10	10	10	10

Figure 18: Nuclear hydrogen production parameters for 4 cases [8]

In cases 1, 2, and 3, conventional low-temperature electrolyzers (CE) are coupled with APWR at different plant capacities, while case 4 integrates high-temperature electrolyzers with HTGR. For the APWR, three cases starting with 359.48, then 718.96, and 1117.05 MWe, are entirely dedicated to hydrogen production. In the case of HTGR, a 510 MWth is dedicated to supplying the required heat by the high-temperature electrolyzer while the electricity is purchased.

Hydrogen storage and transportation are also considered. The storage and transportation cost parameters used for this analysis are based on HEEP's database and are presented in Figure 19 and Figure 20.

Hydrogen storage plant	Compressed Gas	Liquefaction	Metal Hydrides
Storage capacity (kg)	7.52E+06	8.68E+06	7.52E+06
Compressor cooling water (Lit/hr)	2.33E+06	3.23E+07	2.89E+05
Electricity requirement (KWe)	1.02E+05	5.17E+05	1.34E+07
Overnight capital cost ($)	6.54E+08	5.34E+08	1.65E+10
Compressor operating cost ($)	5.38E+07	2.72E+08	0.00E+00
Other O&M cost (% of capital cost)	5	0	0
Decommissioning cost (% of capital cost)	1	0	0

Figure 19: Storage economic parameters [8]

Transportation method	Pipeline	vehicle
Distance for transport (km)	500	500
Overnight capital cost ($)	2.39E+08	6.71E+08
Electricity charges ($)	6.20E+06	–
Fuel cost & driver's pay ($)	–	7.54E+08
Other O&M cost (% of capital cost)	1	0.1
Decommissioning cost (% of capital cost)	1	0.5

Figure 20: Transportation economic parameters [8]

Additionally, financial parameters are provided in Figure 21 .

Parameters	Default value
Discount rate (%)	5%
Inflation rate (%)	1%
Equity component (%)	70%
Debt component (%)	30%
Borrowing interest (%)	10%
Tax rate (%)	10%
Depreciation period (years)	Depends on operating period Min 20 yrs and Max 40 yrs

Figure 21: Finance details [8]

The nuclear hydrogen production plant's chronological data are presented in Figure 22 . These parameters are considered for evaluating the cost of all nuclear power plants.

Event	Period (Yrs.)
Construction	5
Operation	40
Cooling before decommissioning	2
Decommissioning	10
Refurbishment	1
Spent fuel cooling	2
Waste cooling	10

Figure 22: Chronological details [8]

4.6.2 Comparison between nuclear and non-nuclear sources

In addition to studying the impact of nuclear hydrogen production scale on the cost, the current analysis shows three additional non-nuclear cases developed to measure the cost considering the same electrolysis technologies powered with electricity purchased at a constant rate from solar PV, wind, and grid. These cases are presented according to the energy source in Figure 23.

Parameter	APWR360	HTGR240	Grid	Solar	Wind
Thermal rating (MWth/unit)	1089	633.33			
Heat for H2 plant (MWth/unit)	0	54.6			
Electricity rating (MWe/unit)	359.48	185.07			
Number of units	2	3			
Initial fuel load (kg/unit)	27,000	14,000			
Annual fuel feed (kg/unit)	9000	5000			
Overnight Capital cost (USD/unit)	3.16E+09	4.02E+08			
Capital cost fraction- electricity generating infrastructure (%)	10	25			
Fuel cost (USD/kg)	1850	3660			
O&M cost (% of capital cost)	1.66	5.8			
Decommissioning cost (% of capital cost)	2.8	11.7			
H2 Production Plant	CE04	HTSE04	CE04	CE04	CE04
H2 generation per unit (kg/yr)	1.26E+08	1.26E+08	1.26E+08	1.26E+08	1.26E+08
Heat consumption (MWth/unit)	0	163.78	0	0	0
Electricity required (MWe/unit)	719	555.21	719	719	719
Number of units	1	1	1	1	1
Overnight Capital cost (USD/unit)	4.23E+08	4.59E+08	4.23E+08	4.23E+08	4.23E+08
Energy usage cost (USD)	0.00E+00	0.00E+00	3.02E+08	1.47E+08	1.25E+08
Other O&M cost (% of capital cost)	4	17.23	4	4	4
Decommissioning cost (% of capital cost)	10	10	10	10	10

Figure 23: Hydrogen production by electrolysis using different energy sources [8]

The electricity rates for wind, solar PV, and grid are based in Saudi Arabia, and the rates considered for analysis are given in Figure 24.

Power source	Rate $/kWh	Reference
Grid power (industrial tariff)	0.048 (0.18 SAR/Kwh)	[28]
Skaka solar power	0.0234	[29,30]
Dumat Al-Jandal wind power	0.0199	[31,32]

Figure 24: Electric energy cost in Saudi Arabia [8]

4.7 Results and Discussion

The analyses of the different cases shown in Figures 18 and 23 were carried out using HEEP, focusing on a key objective: determining the cost of hydrogen production. These analyses aim to answer two main questions: firstly, how does the cost of producing one kilogram of hydrogen change with varying scales of nuclear facilities? Secondly, how do the costs of hydrogen storage and transportation contribute to overall production costs, and how do these figures compare to those of other technologies?

In case 1, the APWR reactor generates 6770 MWth of thermal power and provides a net electrical output of 2234 MWe. The power conversion system, which converts the thermal energy from the reactor into electricity, operates at a conversion efficiency of around 32-33%. Each unit generates 1117 MWe, which is used to power low-temperature electrolyzers to produce hydrogen at a rate of 12 kg/s. The produced hydrogen is compressed to 20 MPa for storage, requiring approximately 102 MWe, while pipeline transportation needs an additional 11.8 MWe. Both the storage and transportation systems are powered by the grid, with electricity priced at 0.06 $/kWh.

For cases 2 and 3, the production scale is smaller, with electric power outputs of 360 MWe and 720 MWe, producing 4 kg/s and 8 kg/s of hydrogen, respectively.

In case 4, a High-Temperature Gas-cooled Reactor (HTGR) is paired with high-temperature steam electrolysis (HTSE). Here, the reactor supplies heat for the electrolysis process, and the electricity required for hydrogen production is sourced from the grid at 0.06 $/kWh.

The results of the analysis of the cases presented in Figure 18 are shown in Figure 25. The hydrogen production costs are detailed by percentage, showing the hydrogen cost breakdown between the nuclear power production, hydrogen generation process, storage, and transportation for the cases considered.

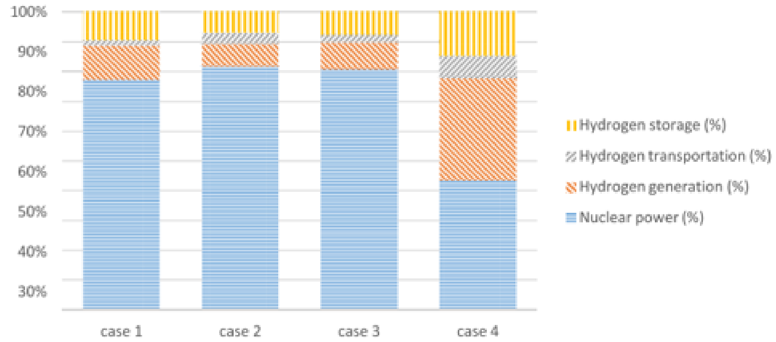

Figure 25: Distribution of hydrogen production cost for the different cases [8]

The Figure 25 shows that, in the cases of APWR, about 80% of the cost is attributed to nuclear power; while the remainder 20% is distributed among hydrogen generation, storage, and transportation. However, in the HTGR case, the cost percentages of nuclear power and hydrogen generation are comparable and add up to about 80% compared to other options. This means that the cost of producing hydrogen using HTGR integrated with HTSE can reduce the cost of hydrogen production by 20%.

Figure 26 compares nuclear hydrogen production costs considering three storage options, i.e., CG, LQ, and MH, for the four cases. As the figure shows, there is a slight difference between CG storage and LQ, where the CG is better in cases 1 and 2 and almost the same in cases 3 and 4; while the MH method is significantly higher in all four cases.

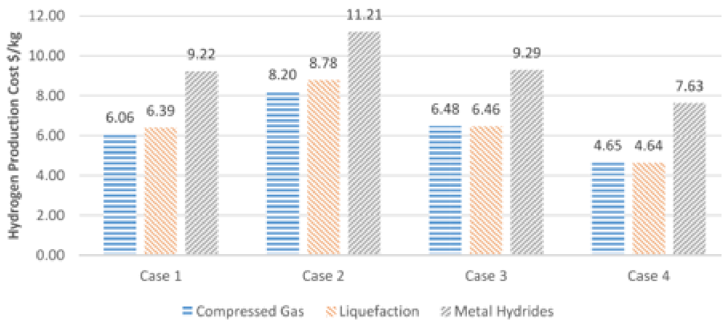

Figure 26: Hydrogen production cost for the different cases and storage options [8]

In this figure 26, the impact of increasing the scale of hydrogen production is evident. For example, the cost of hydrogen production and storage using compressed gas (CG) drops from $8.2/kg at 360 MWe (case 2) to $6.48/kg at 718 MWe (case 3), and further decreases to $6.06/kg at 1117 MWe (case 1). In case 4, where grid electricity is used, the lowest cost for hydrogen production and storage is achieved.

Overall, nuclear hydrogen production costs vary between $4.6 and $8.2/kg for compressed gas storage, while metal hydride (MH) storage, which is more expensive due to costly alloys and complex equipment, ranges from

$7.6 to $11.2/kg.

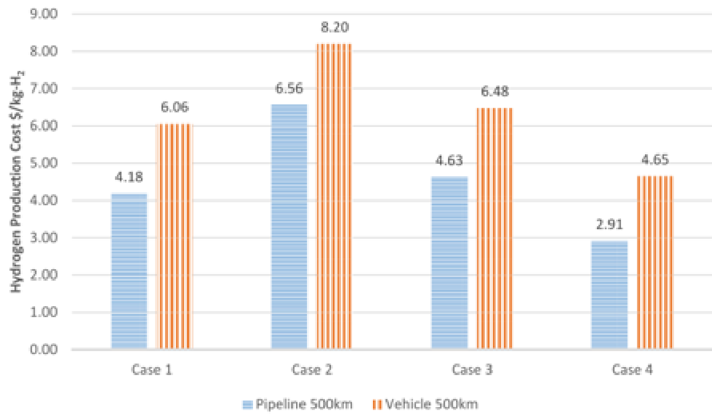

Figure 27: Hydrogen production cost for the different cases and storage options and transportation methods [8]

Figure 27 demonstrates a comparison of the system scale cases, including the transportation methods. It is clear that the pipeline method has a lower cost than the vehicle due to the fuel cost and driver's pay for the vehicle, while in the pipeline system, only electricity is required for the compressors.

To compare the costs of nuclear hydrogen production with non-nuclear methods, both conventional electrolysis (CE) and high-temperature steam electrolysis (HTSE) are analyzed, using five different energy sources: APWR, HTGR, grid electricity, solar PV, and wind, as outlined in Figure 23.

In the APWR case, the nuclear reactor supplies the CE hydrogen plant with the required electricity. For the HTGR case, both heat and electricity are needed for HTSE hydrogen production, so the HTGR reactor provides both. In the grid case, the hydrogen plant draws electricity directly from the grid. The solar and wind cases rely on renewable power plants to supply electricity to the CE hydrogen plant.

The nuclear plants (APWR and HTGR) are assumed to be located near the hydrogen plants, while in the grid, solar, and wind cases, the power sources may be farther away. However, the same CE hydrogen plant with a production rate of 4 kg/s is used for all cases. The input electric power is set at 719 MW, except for the HTGR case, which supplies part of the energy as thermal power (163 MW) and the rest as electricity.

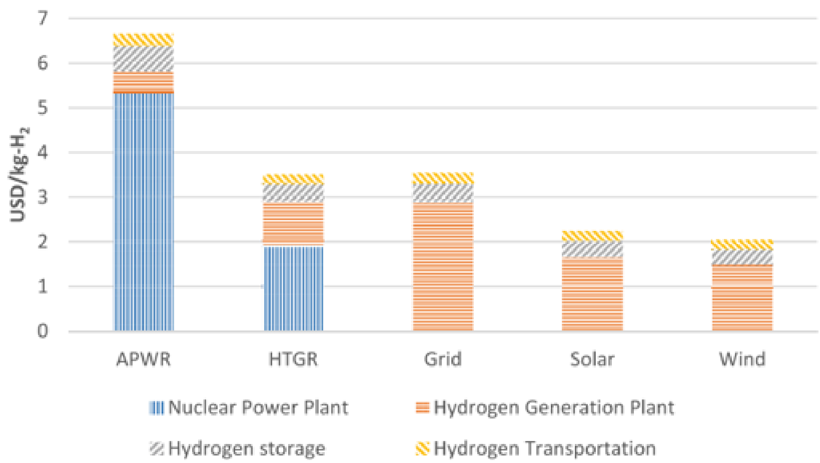

Figure 28: Hydrogen production cost for the different sources [8]

The results in Figure 28 illustrate the hydrogen production costs for the scenarios outlined in Table 7. These costs include expenses for power generation, hydrogen production, storage, and transportation. As shown, renewable energy sources have the lowest hydrogen production costs, with wind power being the cheapest at $2.05 per kg-H, slightly lower than solar power, which costs $2.24 per kg-H. It's important to note that these costs are based on the electricity rates for wind and solar PV presented in Figure 24.

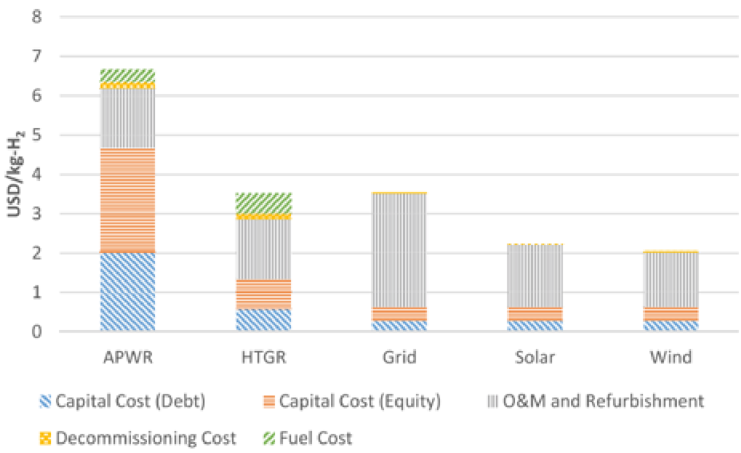

Figure 29: Financial costs associated with hydrogen production for the different sources [8]

Figure 29 shows the cost breakdown for different cases in the study. Operation and Maintenance (OM) and refurbishment costs are almost the same in all cases except for grid electricity, where the high electricity price makes OM the highest, accounting for 81% of the total cost. For the APWR reactor, OM is the lowest at 23%, while it's 44% for the HTGR, and increases to 70% and 67% for solar and wind cases, respectively.

The capital costs are highest in the APWR case, making up 30% and 40% for debt and equity. In contrast, grid electricity has the lowest capital costs, contributing only 8% and 10% to the total hydrogen cost. Decommissioning costs have a minor impact on total production costs, and fuel costs account for 5% of the total cost for APWR and 14% for HTGR.

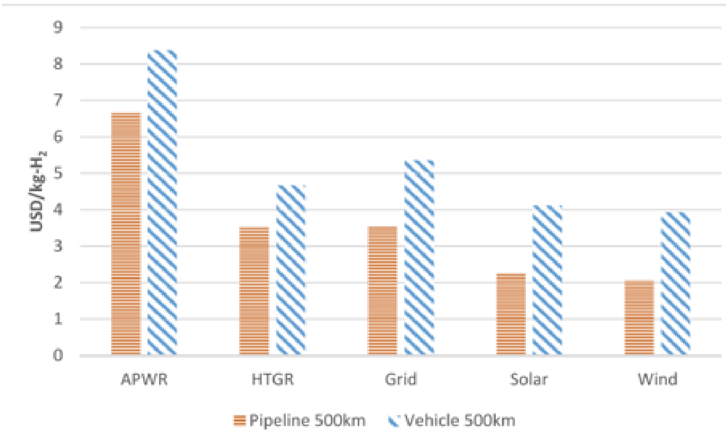

Figure 30: Hydrogen production cost for the different sources and transportation methods [8]

Figure 30 shows the costs of hydrogen production for two transportation methods when combined with a compressed gas (CG) storage plant, based on a distance of 500 km for both vehicle and pipeline transport. The results indicate that pipeline transportation is cheaper than vehicle transportation, but it depends on having a pipeline infrastructure, which is not always available. The pressure of the hydrogen delivered to the end user differs depending on the method: pipeline transport delivers hydrogen at 5 MPa, while vehicle transport assumes a pressure of 20 MPa for compressed gas.

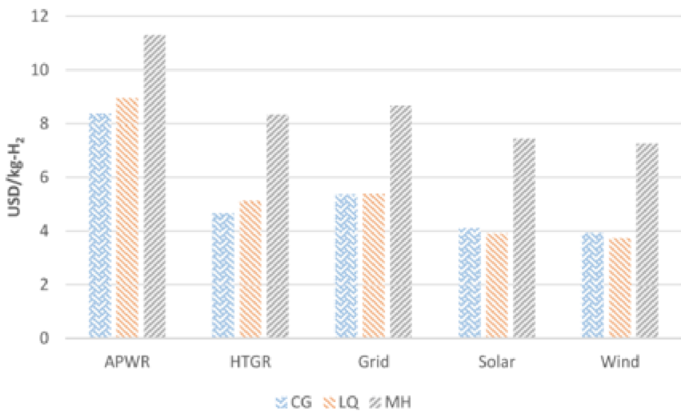

Figure 31: Hydrogen production cost for the different sources and storage options [8]

For the storage options, Figure 31 compares the different storage options: CG, LQ, and MH. The transportation method used in this section is by vehicle. It is clearly noticed that the compressed gas option is the lowest cost while the metal hydride is the most expensive method; except for the solar and wind cases, the liquefaction is slightly better.

Reference and year	H_2 cost ($/kg$H_2$)	Energy cost ($/kWh)	Electrolysis technology	Energy source	Notes
[18], 2020	2.118−2.261	0.063−0.079	AWE	Wind	The research didn't consider the cost of the storage and transportation of the hydrogen
[36], 2019	2.6−12.3	0.01−0.183	PEM	Grid	The cost of hydrogen depends on several factors like the use of the storage and transportation, the year, the state
[37], 2020	6.5−7.58		PEM	Solar (PV)	The system considered the storage but not the transportation of the hydrogen, and the cost depends on applying the batteries or not for the PV panels
[38], 2017	3.18−6.17		Electrolysis	Nuclear (PWR)	The study applied the cost of storage and transportation, and the cost depends on the type of the storage
[11], 2014	3.23−8.27	0.049	AWE, HTSE, HyS	Nuclear (PMR, PBR, HTGR)	The hydrogen cost depends on several factors as reactor type, hydrogen generation type, the type of storage, distance, and the type of the transportation
Current study, 2023	4.18−11.31	0.101	AWE	Nuclear (APWR)	The cost depends on some factors such as the storage type, the transportation method
	2.91−8.34	0.057	HTSE	Nuclear (HTGR(	
	3.55−8.67	0.048	AWE	Grid Electricity	
	2.05−7.26	0.0199	AWE	Wind power	
	2.24−7.44	0.0234	AWE	Solar PV power	

Figure 32: Hydrogen production cost with different sources of electricity [8]

In Figure 32, the findings of this study are compared with other research, focusing on electricity type and cost, electrolysis methods, and assumptions from previous studies. The table reinforces the well-known conclusion that electricity costs are a key factor in determining the cost of hydrogen produced through electrolysis. However, factors like production scale, energy storage, and system integration are also crucial in lowering hydrogen production costs.

5 Future Perspectives

5.0.1 Policies

Global public opinion and environmental concerns have shaped a variety of nuclear energy strategies in different countries. National responses to the Fukushima accident differed; some countries took steps to phase out nuclear energy, while others reaffirmed their commitment to it, frequently citing the safety and environmental benefits of nuclear power [20]. Arguments in favour of nuclear energy have frequently included environmental concerns, with supporters highlighting the technology's ability to mitigate climate change [21]. As a result of perceived risks and political situations, anti-nuclear protests have grown to be a significant force in many democracies [22]. Policy, public opinion and environmental campaigning continue to interact to shape nuclear energy initiatives. However, the effect of these demonstrations differs greatly based on the political climate of the given time. Despite popular rejection, support for nuclear energy generally persists in totalitarian nations [22].

Despite the fact that national policies and regulations govern hydrogen, international cooperation is essential to the market's expansion, in order to promote private investment and unify standards. Many regional and international projects are already in progress, including: [23]

- Mission Innovation (MI), a global program with the objective to lower the cost of clean hydrogen such that its production is profitable by 2030;
- With an emphasis on the research and application of fuel cell and hydrogen technologies, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) unites 22 nations in an effort to accelerate the shift to cleaner and more efficient energy systems;
- The Technology Collaboration Program on Advanced Fuel Cells (AFC TCP) of the International Energy Agency (IEA) encourages the worldwide advancement of fuel cell technologies and seeks to lower obstacles to their commercialization.

For nuclear energy to be considered a clear option in hydrogen production, it is important that these initiatives include projects and programs aimed at this integration. In this regard, some recommendations should be considered: [23]

- Plans That Are Technologically Neutral: Policies involving hydrogen should cover all low-carbon methods of producing hydrogen, avoiding classification based only on colour schemes and concentrating on carbon footprints;
- The production of hydrogen using nuclear energy should be specifically mentioned in hydrogen plans as a zero-carbon pathway, with defined targets and indications for its achievement;

- Research and Development (R&D) Investment: By 2028, specific funds should be allocated to the development of nuclear technologies that allow for the large-scale production of hydrogen from existing and advanced reactors;
- Production Incentives: Offer tax breaks and other financial incentives, such as tax credits, loan guarantees and special tariffs, to companies that create nuclear hydrogen;
- End-User Incentives: Provide tax breaks to businesses that utilize low-carbon hydrogen and temporarily subsidize the acquisition of nuclear hydrogen to encourage its industrial application.

It is expected that these recommendations will accelerate the integration of nuclear energy-based hydrogen generation.

5.0.2 Challenges and Advantages

Considered a versatile energy vector, hydrogen is viewed as one of the ways to decarbonize some heavy industries, including transportation and the so-called ”hard-to-abate” sectors that significantly rely on fossil fuels. Nuclear-powered hydrogen production makes this shift easier. However, there are several social, economic and technical obstacles to overcome before a nuclear hydrogen production system can be put into place.

One of the primary benefits is that, by employing advanced nuclear reactors and the several previously described methods, including electrolysis and thermochemical processes, hydrogen can be produced without releasing any pollutants [24][25]. In order to meet the rising energy demands, nuclear energy also offers a reliable and high-capacity source to enable hydrogen production [26]. However, the implementation of this technology faces challenges such as high initial and operational costs, and public acceptance [27].

Main Advantages of Nuclear Hydrogen Production

1. Clean production: Hydrogen can be produced using energy obtained from nuclear reactors without the carbon emissions that come with using conventional fossil fuel-based techniques [25];
2. Large-scale production: advanced nuclear reactors can guarantee the generation of hydrogen in amounts adequate to satisfy high energy demands [24]);
3. Variety of available methods: Proton exchange membrane (PEM) electrolysis and the sulfur-iodine process are two practical methods for producing hydrogen [28].

Main Obstacles of Nuclear Hydrogen Production

1. High Investments: It requires significant investments and takes years to become operational. Despite the high energy generation capacity, financial return is not immediate as it also takes time [28].
2. The issue of public acceptance is another one that cannot be disregarded. Safety and radioactive waste disposal are two issues that continue to be obstacles to nuclear energy. Any mishap or mistake causes a powerful reaction that restricts investment.

3. Finally, there is the crucial requirement for excellent and secure infrastructure in addition to specialized technical knowledge, both of which have an effect.

In the end, any developments in the nuclear + hydrogen field will be closely linked to advancements in technology, public acceptance and supportive governmental regulations.

5.0.3 Nuclear Hydrogen Demonstration Projects

Currently there are no nuclear hydrogen projects with fully commercialized systems in operation, but there are several projects in the pilot phase, some of them have feasibility studies underway, and others in operational testing.

At the beginning of the 2010s decade, China and Russia started approaching nuclear-assisted steam reforming of natural gas, which is a good development but not the focus of our work. In places like Europe, Japan or Canada they began some experimental activities to test hydrogen production using Low temperature and high-temperature electrolysis.[14]

According to The Global Hydrogen Review of 2021, there are around a dozen demonstration projects exploring using nuclear power for hydrogen production through water electrolysis (combined electrolyser capacity of 250 MW), in Canada, China, Russia, the United Kingdom and the United States. [29]

The Nuclear Hydrogen initiative is a nonpartisan, global collaboration of more than 50 companies, academic institutions, government agencies, and non-profit organizations did a report in 2022 with a lot of takes on this topic, which included a summary list of current national hydrogen roadmaps and strategies from selected countries/regions with nuclear infrastructure, so with that, we made a map and a resume table of the countries that have nuclear hydrogen demonstration projects or research.[30]

Figure 33: Nuclear Hydrogen demonstration projects locations

Brazil	Canada	China	France	Japan
Project at **Braskem** and **Eletronuclear NPP** to capture and use the hydrogen being generated as a by-product of a chemical process.[31]	1. A feasibility study for a Hydrogen Hub in Toronto will assess the potential of producing hydrogen through electrolysis, powered by a surrogate heat source to simulate a nuclear power plant supported by Bruce Power[32]. 2. Ontario Tech University[33] advancing thermochemical production of H2 studies at CNL.	China's Institute of Nuclear and New Energy Technology piloting several lab-scale projects, including hydrogen production via high-temperature electrolysis and thermochemical splitting.[13]	EDF is planning hydrogen production at its existing fleet, but no specific plans announced.[13]	Japan Atomic Energy Agency (JAEA) is pursuing the demonstration of nuclear hydrogen production through thermochemical splitting at an HTGR.[34]
Russia	**South Korea**	**United Arab Emirates**	**United Kingdom**	**United States**
In 2019, Rosatom outlined its HTR program, focusing on hydrogen production by catalytic conversion of methane with utilization of CO_2 and commissioning HTR plants for this by 2030.[30]	First Nuclear Hydrogen Production Plant by 2027, by Hyundai Engineering & Construction, Samsung C&T, Doosan Energy, and Korea Hydro & Nuclear Power (KHNP). The 10 MW plant will employ "low-temperature water electrolysis" producing more than four tonnes of pink hydrogen daily.[35]	ENEC has made statements about hydrogen production at Barakah NPP. ENEC and EDF have announced plans to cooperate on nuclear energy R&D under an MoU focusing on hydrogen production.[36]	Bay Hydrogen Hub proposes to build a co-located solar electrolytic cell (SOEC) electrolyzer at Heysham Power Station in Lancashire. The EDF plant would produce 1.25 MW quantities directly stored, delivered via pipeline, or converted to ammonia. This would be transferred, by ship, to Hanson's **Cement** plant in North Wales.[37]	1. Energy Harbor, Xcel Energy, and PSE are spearheading a multi-million-dollar project at Davis-Besse NPP to produce hydrogen using polymer electrolyte membrane technology. 2. Exelon gathered funding from the DOE's H2@Scale program for hydrogen production projects at Nine Mile Point and electrical systems from Idaho and National Laboratories. 3. Support to work by **INL** to analyze the viability of nuclear energy to aid solar and wind installations.[30]

Table 2: Overview of Nuclear Hydrogen Projects by Country

These projects show that the nuclear hydrogen sector is still in its early stages, with no fully commercialized systems currently in operation. However, substantial work is being done to move from pilot and demonstration phases to commercial-scale production. The success of these projects depends on further technological development, cost reductions, regulatory support, and infrastructure investment. If these hurdles are overcome, some of these pilot projects could scale up and become commercially viable within the next decade.

6 Conclusion

Hydrogen demand around the World is increasing at a very fast rate. To keep up with this rate, there will be a need for large scale production of hydrogen without the compromising intermittency of renewable energy. Nuclear power has the potential to produce hydrogen at high efficiencies and competitive costs while still being a clean method and should be present on goals for hydrogen production as a zero-carbon pathway.

High-temperature electrolysis and thermochemical cycles, namely the Sulfur-Iodine cycle and the Hybrid Sulfur cycle are a few of the methods that will likely lead the way for nuclear hydrogen production, even though they are still not fully commercialized and still need some material improvements.

Nuclear will be in the World's future energy mix and a general acceptance from the population is needed. Collaboration between governments and companies will allow this technology to thrive and pave the way for cleaner hydrogen production.

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