POLITECNICO DI TORINO

Master’s Degree in Sustainable Nuclear Energy
A.A. 2025–2026
Graduation Session March 2026

HYDROGEN PRODUCTION FROM NUCLEAR FISSION PLANTS: TECHNICAL-ECONOMIC EVALUATION OF SMR-LWR AND HTGR

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Ai miei genitori,

con infinita gratitudine.

Abstract

The need to decarbonize industries and ensure energy security has also focused attention on hydrogen production using nuclear energy. In this context, this thesis aims to develop a comparative technical-economic analysis of the main nuclear technologies used in hydrogen production, with a focus on Small Modular Reactors with light water (SMR-LWR) and High Temperature Gas cooled Reactors (HTGR), which also include other subcategories such as VHTR and HTTR. The analysis is based on the identification of the main technical and economic parameters that influence the choice of reactor and hydrogen production process. The link between the thermodynamic characteristics of the reactor and the production paths useful for this new source is examined. By comparing the various reactor configurations, the conversion efficiency of the reactors and the investment costs are evaluated. Particular attention is also paid to the implications in terms of safety, technological maturity, and risk. The results show that high-temperature reactors offer a potential competitive advantage in hydrogen production thanks to the direct use of process heat, although there are greater uncertainties at the technological and financial level. SMR-LWRs, despite being much more technologically mature and presenting fewer engineering risks, are more limited in terms of overall efficiency. The thesis therefore provides a structured framework for evaluating the various nuclear options for large-scale hydrogen production in the medium to long term.

Contents

Introduction

The current energy landscape aims to combat climate change and reduce net greenhouse gas emissions to zero by 2050. To achieve this goal, in line with the Paris Agreement, a transition is underway that requires the gradual abandonment of fossil fuels. In this scenario, nuclear energy plays a key role. Unlike renewable sources, whose production is strictly dependent on weather conditions, nuclear energy guaranties a massive and uninterrupted supply of electricity 24 hours a day. This stability makes it an ally that can compensate for the intermittency of renewable sources, ensuring the security and reliability of the entire electricity grid. However, decarbonizing electricity production alone is not enough to improve the climate situation, as action must also be taken in the "hard-to-abate" sectors—such as heavy industry, steel, chemicals and long-distance transport—which are extremely difficult to electrify directly. For these challenges, hydrogen is emerging as an energy carrier of the future. However, most of the hydrogen produced globally comes from fossil fuels. Therefore, for hydrogen to become a real solution, its production methods must be transformed. In this context, the potential use of nuclear energy for the production of clean hydrogen emerges. Using the electricity and process heat generated by reactors, it is possible to produce so-called "pink hydrogen" continuously and with zero emissions. The main objective of this thesis is to assess the technical and economic feasibility of this integration. Specifically, the study compares two different nuclear technologies coupled with different hydrogen production processes: small modular reactors (SMR-LWR) and advanced high-temperature reactors (HTGR), analyzing their coupling with electrolysis processes and thermochemical cycles. For purely comparative purposes, heavy water reactors were also studied, and blue hydrogen, which is produced from fossil sources but with CO2 capture, was used as a baseline. Using the HEEP (Hydrogen Economic Evaluation Program) software developed by the IAEA, various operating scenarios were defined and simulated. The analysis aims to quantify thermodynamic performance and examine cost items (initial investments and operating expenses) in detail to calculate the levelized cost of hydrogen (LCOH). The results of this study will make it possible to identify the most competitive nuclear technology configuration, demonstrating how new-generation reactors can represent a potential solution to economically advantageous and truly sustainable hydrogen production.

State of the Art of Hydrogen

This first chapter aims to provide a comprehensive and detailed overview of hydrogen, outlining its fundamental role as an energy carrier. First, the main chemical and physical properties of the element are analyzed, along with the classification that allows hydrogen to be distinguished based on its primary sources and the technologies used for its generation. Next, an overview of current global production is presented, followed by an in-depth analysis of the logistical challenges. In addition, the main methods related to both transport and storage are explored. Finally, the chapter concludes with an examination of the technological and infrastructural limitations, accompanied by a review of European regulations and strategies, which is essential for understanding the future directions of development and investment in the sector.

1.1 Chemical and Physical Properties of Hydrogen

Hydrogen is the first element in the periodic table and is also the lightest. It consists of one proton and one electron. Under standard temperature and pressure conditions, it occurs as a diatomic molecule – H_2 – and is a colorless, odorless, and non-toxic gas.

At an atomic level, natural hydrogen is composed of a mixture of three isotopes, which differ by the number of neutrons in the nucleus [1]:

- **Protium** (^1H): the most stable and abundant isotope, with a diffusion of 99.98%, consisting of a single proton and an electron.
- **Deuterium** (^2H): it is weel known as heavy hydrogen, its nucleus has one proton and one neutron.
- **Tritium** (^3H): it is radioactive and unstable isotope, which has two neutrons in the nucleus.

Furthermore, it is the most abundant element in the observable universe (it constitutes about 75% of normal matter), but on Earth it is practically impossible to find it in a free gaseous state. Due to its lightness, it tends to escape Earth's gravitational pull. For this reason, hydrogen is almost exclusively found combined with other chemical elements

[2]. The most common aggregations include water (H_2O) in combination with oxygen, hydrocarbons such as methane (CH_4) in combination with carbon, and ammonia (NH_3) in combination with nitrogen [2].

Since obtaining pure hydrogen requires the breaking of molecular bonds through chemical or physical processes that consume energy, it is defined as an "energy carrier" and not as a primary energy source that can simply be extracted from nature [2].

From a thermodynamic point of view, hydrogen has the highest energy-to-mass ratio of all known fuels. The US Department of Energy (DOE) reports a Lower Heating Value (LHV) of approximately 120 MJ/kg and a Higher Heating Value (HHV) of approximately 142 MJ/kg for hydrogen [3]. This means that, weight for weight, one kilogram of hydrogen contains almost three times the energy of one kilogram of diesel or gasoline [4].

However, this very high gravimetric energy density (per kilogram) is balanced by an extremely low volumetric energy density (per liter). As a result, it occupies immense volumes.

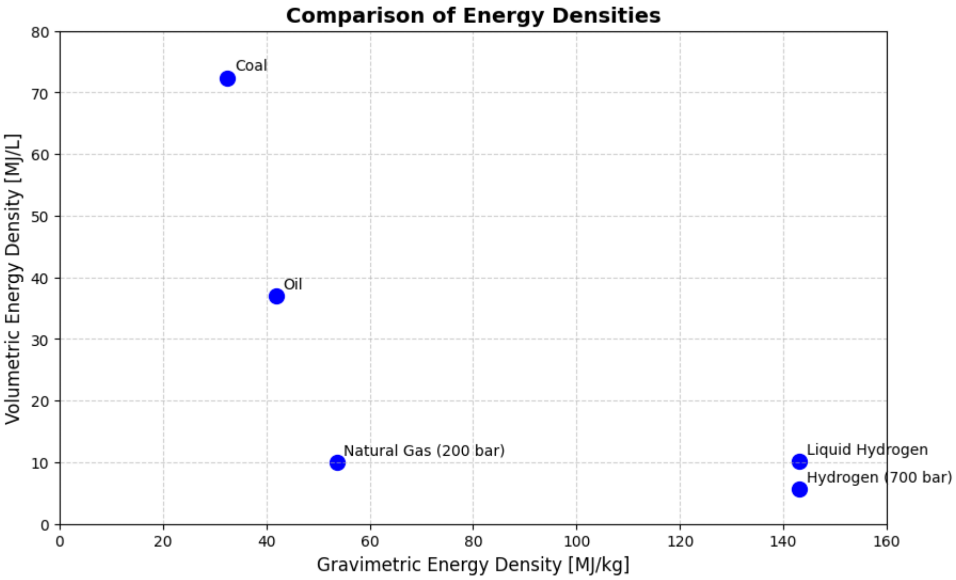


Figure 1.1: Comparison of Gravimetric and Volumetric Energy Densities of various fuels.

When left in gaseous form under normal temperature and pressure (NTP) conditions, hydrogen has a density of only $0.0838\,\mathrm{kg/m^3}$ [3].. To overcome this logistical limitation related to storage and transport, it must be compressed to very high pressures (up to 700 bar) or liquefied. The liquefaction process, in particular, is highly energy-intensive, as hydrogen has one of the lowest boiling points in nature: precisely 20.28 K (-252.87 °C) at a pressure of 1 atm [5].

Finally, hydrogen has a very wide flammability range when mixed with air, varying from 4.0% to 75.0% by volume [3]. On the one hand, this makes it a highly flammable gas in enclosed spaces, but on the other hand, its extreme buoyancy plays in favor of safety in open environments: in the event of a leak, hydrogen disperses very quickly upwards at extremely high speeds, drastically reducing the risk of prolonged and localized explosions compared to traditional fossil fuels [3]. Since hydrogen is an energy carrier, the environmental impact of its production varies significantly depending on the primary energy source and the specific technology used. These differences have led to a universally adopted color classification system, which will be detailed in the next section.

1.2 The Colors of Hydrogen

Hydrogen is a colorless gas. However, in industry and engineering, a classification system is conventionally used that distinguishes this gas by colors that identify not only the primary source from which the carrier was obtained, but also the extraction technology used and the resulting environmental impact (in terms of greenhouse gas emissions) [6]. As reported by the International Energy Agency (IEA) in its report *The Future of Hydrogen* [7], current global hydrogen production is mainly oriented towards fossil fuels. In fact, approximately 96% of global hydrogen comes from non-renewable sources, of which:

- 48% from natural gas,
- 30% from oil,
- 18% from coal.

Only the remaining 4% is obtained from water electrolysis.

Analyzing the individual categories, **black (or brown) hydrogen** is derived from the coal gasification process.

Gray hydrogen is obtained from natural gas, mainly through the Steam Methane Reforming (SMR) process [6]. To date, gray hydrogen dominates the market, as it is the most economically advantageous alternative [7]. Its price is closely linked to that of methane, which in this case is the starting raw material. Considering a standard cost of natural gas of around €25/MWh, gray hydrogen costs around €1.5/kg. Being a very mature technology, it has standardized logistics and extraction costs. The disadvantage of this type of process is its significant environmental impact, as hydrogen production generates large amounts of carbon dioxide released directly into the atmosphere [6].

Blue hydrogen is one of the strategies that mitigates emissions. This vector is produced from the same fossil sources as gray hydrogen, but the process is coupled with carbon capture and storage (CCS) systems. In this way, most of the CO_2 emitted is sequestered downstream of the process and stored in dedicated geological sites [6]. Economically, the implementation of capture systems entails an increase in costs of approximately €0.5/kg compared to gray hydrogen, bringing the total to approximately €2/kg [7]. The long-term outlook is for this surcharge to fall to €0.25/kg, but it is important to note that recent geopolitical crises, causing sharp fluctuations in the price of natural gas, make costs highly unstable.

One technology considered an excellent bridging technology for the energy transition is methane pyrolysis, from which **turquoise hydrogen** is derived. In this thermal process, natural gas is split at high temperatures, generating hydrogen gas and carbon in a solid state [6]. The main advantage lies in the absence of direct emissions of gaseous CO_2 and the possibility of reselling the solid carbon as a raw material for other industrial sectors. At present, however, the technology is not mature [6].

Another type of “clean” hydrogen is **green hydrogen**, generated from water split by an electrolytic process powered exclusively by renewable sources (such as wind or photovoltaic). The environmental impact of this vector is zero [6]. The main obstacle to this technology is the operating and installation costs of the electrolyzers. Assuming the use of an offshore wind farm with a load factor of 4000 hours and a generation cost of €50/MWh, green hydrogen currently costs between €4 and €5.2/kg. As the load factor increases, the cost decreases proportionally (€3-3.9/kg). Despite the costs, the European Agenda plans to produce 10 million tons of green hydrogen by 2030, while the China Hydrogen Alliance estimates that by 2050, 70% of China’s H_2 production will be green. In Italy, applications are in their early stages, but there are projects such as the H2 South Tyrol refueling station near Bolzano, which produces green hydrogen using energy from an adjacent hydroelectric plant.

Finally, there is **purple (or pink) hydrogen**, which is obtained from the electrolysis of water using electricity generated by nuclear power plants. Although its diffusion is limited by the energy policies of some countries, the future introduction of fourth-generation nuclear reactors (such as modular reactors) will provide a significant boost to this technology.

1.3 Current Global Hydrogen Production

The current production and demand volumes are analyzed below. According to the Global Hydrogen Review 2025 report published by the International Energy Agency (IEA) [8], global demand for hydrogen reached nearly 100 million tons (Mt) in 2024 and is set to exceed that threshold in 2025, confirming a historical growth trend (Figure 1.2). However, this steady growth is not due to the implementation of climate policies, but rather to traditional industrial applications and macroeconomic trends.

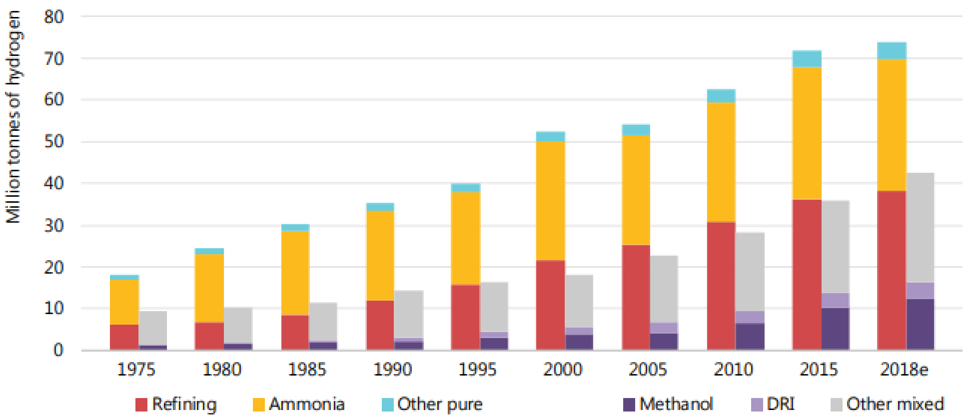


Figure 1.2: Global annual demand for hydrogen since 1975 [7].

Currently, demand for hydrogen is almost exclusively concentrated in historically established sectors. The majority of this energy carrier is used in oil refining processes, ammonia and methanol production, and metallurgical processes. The current value chain is well illustrated in Figure 1.3. In contrast, the adoption of hydrogen in "new applications" crucial to the ecological transition (such as heavy industry, long-distance transport, and energy storage) is still in its infancy and accounts for less than 1% of global demand.

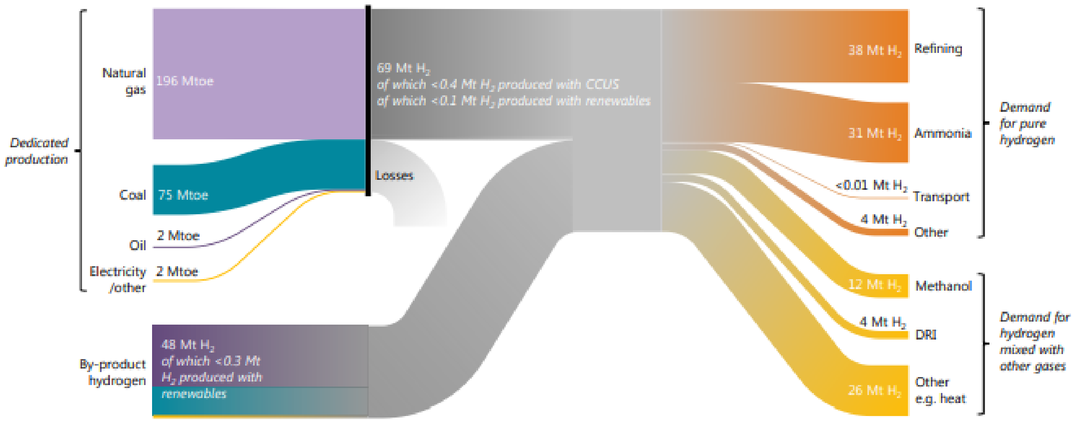


Figure 1.3: Today's hydrogen value chains [9].

Global production is heavily dominated by fossil fuels without an emission abatement systems. In 2024, hydrogen extraction required the consumption of 290 billion cubic meters of natural gas and 90 million metric tons of coal equivalent (Mtce) [8]. The dependence of the market on fossil raw materials without the aid of carbon capture and storage (CCS) systems results in significant direct CO_2 emissions. Low-emission hydrogen (such as green and blue variants) grew by 10% in 2024 and is estimated to reach a production volume of around 1 Mt in 2025; however, it still accounts for less than 1% of total global production.

Despite the current dominance of fossil-based hydrogen and the challenges associated with the high costs of clean alternatives, the sector shows significant signs of future development. According to IEA estimates [8], based solely on projects currently operational, under construction, or that have already reached a final investment decision (FID), low-emission hydrogen production could exceed 4.2 Mt per year by 2030. In addition, global installed electrolyzer capacity is growing rapidly from a low base, with China currently leading the global market in terms of both installations and manufacturing capacity.

1.4 Hydrogen Logistics: Storage and Transport

To build a real hydrogen economy, producing the gas is not enough. The gas must be moved from the production plant to the final user and stored safely until it is needed. This entire process is called hydrogen logistics. Because hydrogen is the lightest element in the universe and has a very low volumetric energy density, its transport and storage are technically difficult and expensive [8].

Today, the more used methods to handle hydrogen are based on its physical state or chemical bonds: compressed gas, cryogenic liquid or bound inside other molecules, as illustrated in Figure 1.4.

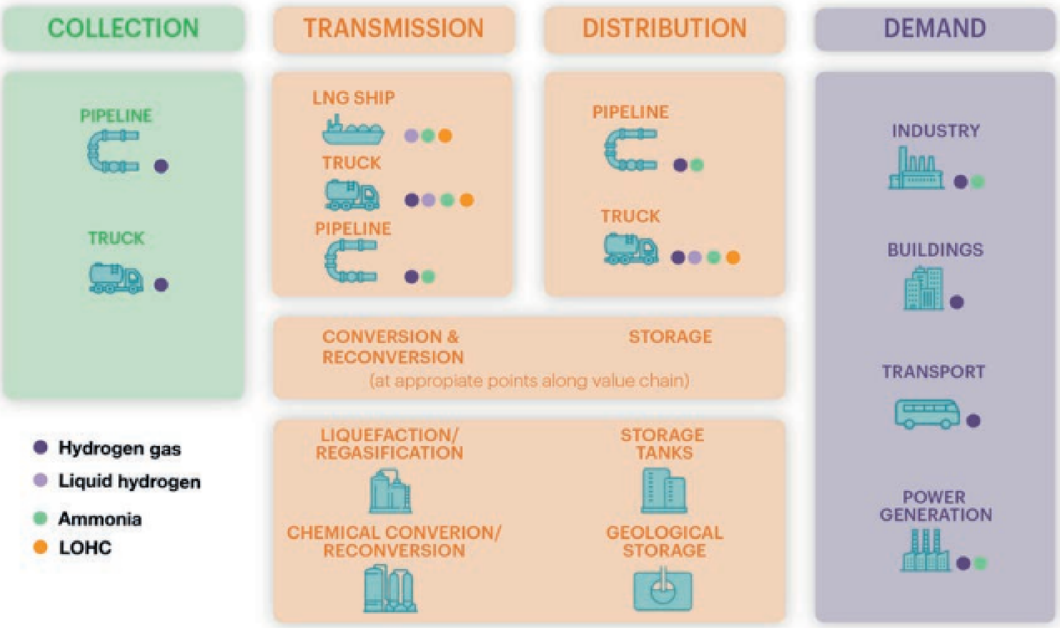


Figure 1.4: Transmission, distribution and storage elements of hydrogen value chains [7].

1.4.1 Compressed Gaseous Hydrogen

The most common and mature way to store and transport hydrogen is in its gaseous form. To reduce the volume and pack more energy into a given space, the gas must be compressed at very high pressures, usually between 350 and 700 bar [3].

For transport over short or medium distances, the industry uses special trucks called tube trailers. These trucks carry several cylinders full of compressed gas. For long distances and high volumes, pipelines are the best option. However, building a new pipeline network dedicated only to hydrogen requires huge investments. For this reason, many countries are trying to blend small percentages of hydrogen directly into the existing natural gas networks [8].

Regarding storage tanks, there are four main categories on the market, classified from Type I to Type IV. Type I tanks are made entirely of steel: they are cheap but very heavy. Type IV tanks, on the other hand, are made of a plastic liner wrapped in carbon fiber. They are much lighter and can withstand 700 bar of pressure, making them the standard choice for modern hydrogen cars [3].

1.4.2 Cryogenic Liquid Hydrogen

Another option is to cool the hydrogen down to -253 °C (20 K) so it becomes a liquid. Liquid hydrogen has a much higher density than the compressed gas, which means we can transport a lot more energy in the same physical space. This is very useful for long-distance transport using insulated tanker ships or special cryogenic trucks.

However, the liquefaction process has big disadvantages. Cooling the gas to such extreme temperatures requires a huge amount of energy: almost 30% of the energy contained in the hydrogen itself is lost just to run the cooling plant [3]. Also, the storage tanks must be perfectly insulated, similar to a vacuum flask. Even with the best insulation available today, some environmental heat always enters the tank. This causes a phenomenon known as “boil-off”: a small part of the liquid evaporates back into gas, increasing the pressure inside the tank and forcing operators to vent some gas into the atmosphere for safety reasons.

1.4.3 Ammonia, Chemical Carriers and Solid State

Because handling highly compressed or extremely cold hydrogen is complex, scientists are studying other ways to move it. One of the most promising solutions is to convert hydrogen into ammonia (NH_3). Ammonia is a well-known chemical that is already traded globally. It is much easier to liquefy (it only needs -33 °C) and existing ships can easily transport it. Once the ammonia arrives at its destination, it can be "cracked" (decomposed) to release the pure hydrogen again [8].

Other alternatives include Liquid Organic Hydrogen Carriers (LOHCs) and solid-state storage. LOHCs are special oils that can absorb hydrogen and release it when heated. Solid-state storage, instead, uses special metal alloys (metal hydrides) that act like a sponge, absorbing the gas. This method is incredibly safe and works at very low pressures, but the metals are extremely heavy, making this technology better suited for stationary storage rather than vehicles.

1.5 Criticalities and Limitations of Hydrogen

Despite its great potential as a clean energy vector, hydrogen presents several physical and technical problems that need to be solved to ensure a large-scale application.

First of all, safety is a major concern. Hydrogen has a very wide flammability range when mixed with air (from 4% to 75%) and requires very little spark energy to ignite [3]. Because the hydrogen molecule is so small, it can easily leak from standard pipes, seals, and valves.

Another critical issue is known as “hydrogen embrittlement”. When pure hydrogen gas flows through steel pipes at high pressures, its tiny atoms can penetrate the metal structure. Over time, this chemical interaction makes the steel brittle and can cause sudden cracks. Because of this, we cannot simply use all the existing natural gas pipelines for pure hydrogen without making expensive material upgrades or applying special internal coatings.

Finally, the overall energy efficiency remains a strong limitation. Every step of the hydrogen value chain requires energy. When we produce hydrogen, compress it or liquefy it, transport it, and finally convert it back into electricity (for example inside a fuel cell), a significant percentage of the initial energy is lost. This round-trip efficiency problem makes hydrogen logistics one of the biggest engineering and economic challenges for the future energy transition.

1.6 European Hydrogen Strategies and Regulations

To move from theoretical models to a real industrial scale, the hydrogen economy requires a solid legislative framework. The European Union has positioned itself as a global leader in defining the rules, targets, and financial support mechanisms for the transition to clean hydrogen.

The political foundation of this transition was laid with the EU Hydrogen Strategy in 2020. However, the geopolitical energy crisis in 2022 forced the European Commission to accelerate these efforts, resulting in the publication of the REPowerEU plan [10]. This plan sets an ambitious double target for 2030: the European Union aims to produce 10 million tonnes (Mt) of renewable hydrogen domestically and to import an additional 10 Mt from international partners.

To ensure these targets are met, the EU translated the political goals into binding laws through the revised Renewable Energy Directive (RED III), approved in 2023 [11]. RED III introduces mandatory quotas for the member states. For instance, the industrial sector, which currently relies heavily on fossil-based grey hydrogen, is legally required to replace at least 42% of its hydrogen consumption with renewable hydrogen by 2030, and 60% by 2035.

While setting targets is relatively simple, defining what exactly constitutes “green” or “renewable” hydrogen is complex. The European Commission addressed this issue by publishing specific Delegated Acts in 2023 [12]. In the European legal framework, renewable hydrogen is classified as a Renewable Fuel of Non-Biological Origin (RFNBO). To obtain this classification, hydrogen producers must strictly comply with two main rules:

- **The Principle of Additionality**: Producers cannot simply connect an electrolyzer to the existing national electricity grid, because the standard grid mix still contains fossil energy. To label the hydrogen as renewable, the producer must build or directly finance new, dedicated renewable energy installations (such as new wind or solar farms).
- **Temporal and Geographic Correlation**: The hydrogen must be produced during the same time period when the dedicated renewable energy plant is generating electricity (initially calculated on a monthly basis, but moving to an hourly basis by 2030). Furthermore, the electrolyzer and the renewable power plant must be located in the same bidding zone to prevent grid congestion.

Finally, to help the industry overcome the high initial costs, the EU launched the European Hydrogen Bank. This financial instrument uses a fixed-premium auction system. It is designed to cover the “green premium”, which is the price difference between the cheap production of grey hydrogen and the currently higher production costs of renewable hydrogen. Through these regulations and funding mechanisms, the EU aims to create a predictable and secure market for investors.

Hydrogen Production from Nuclear Sources

As seen in the first chapter, dependence on fossil fuels makes the transition to clean hydrogen difficult. Added to this are the intrinsic limitations of renewable energies, such as their intermittency in energy production and high land consumption.

In this scenario, nuclear energy plays an important role because it emerges as a technological and strategic solution. Nuclear reactors not only guarantee continuous baseload electricity production with zero carbon emissions, but also represent a source of large-scale process heat, which is necessary for hydrogen production.

The integration of a nuclear reactor into a chemical plant allows both the electrical and thermal energy of some reactors to be exploited, paving the way for much more efficient methods of hydrogen production than traditional electrolysis. This chapter analyses the technical structure of these systems in detail.

Initially, the main production routes and their respective energy balances and requirements will be explored. Subsequently, the analysis will shift to the engineering challenges associated with the thermal coupling between the nuclear plant and the production plant, with particular attention to the critical role of intermediate heat exchangers. Finally, the fundamental role of the reactor outlet temperature on the overall thermodynamic efficiency of the process will be demonstrated, highlighting the potential of fourth-generation reactors.

2.1 Production Pathways

Direct thermal decomposition of water is unfeasible through industrial processes due to the extremely high temperatures required, equal to or greater than 2500 °C. For this reason, hydrogen production with the aid of nuclear energy is based solely on advanced multi-stage processes, which operate at more manageable temperatures [13]. To date, there are two paths being researched internationally: high-temperature electrolysis (HTSE) and thermochemical cycles.

HTSE is a process that works in reverse to a solid oxide fuel cell (SOFC). It uses a solid ceramic electrolyte, such as yttria-stabilized zirconia (YSZ), to split steam into hydrogen and oxygen ions at temperatures between 750 and 950 °C.

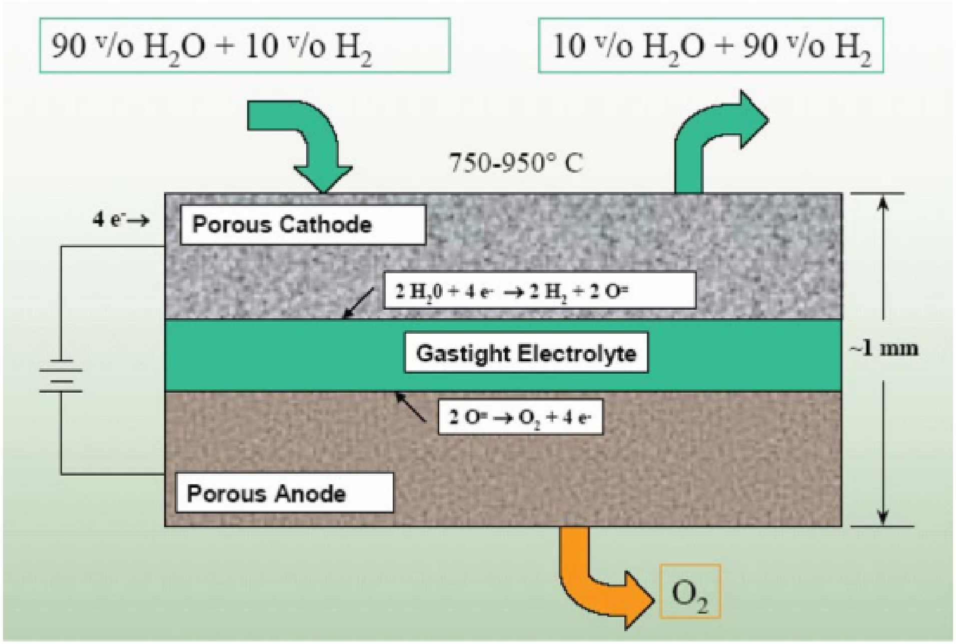


Figure 2.1: Schematic of a planar steam electrolysis cell [13].

Thermochemical cycles, on the other hand, split water through a series of closed-cycle chemical reactions, with the aid of heat supplied by the reactor. In these processes, the intermediate chemical compounds are continuously regenerated and recycled within the plant; among the various configurations are: the sulfur-iodine (S-I) cycle and the sulfur-based hybrid cycle (HyS). Sulfur is chosen because it has a high theoretical efficiency and requires a very low number of reactions compared to the other cycles studied [13].

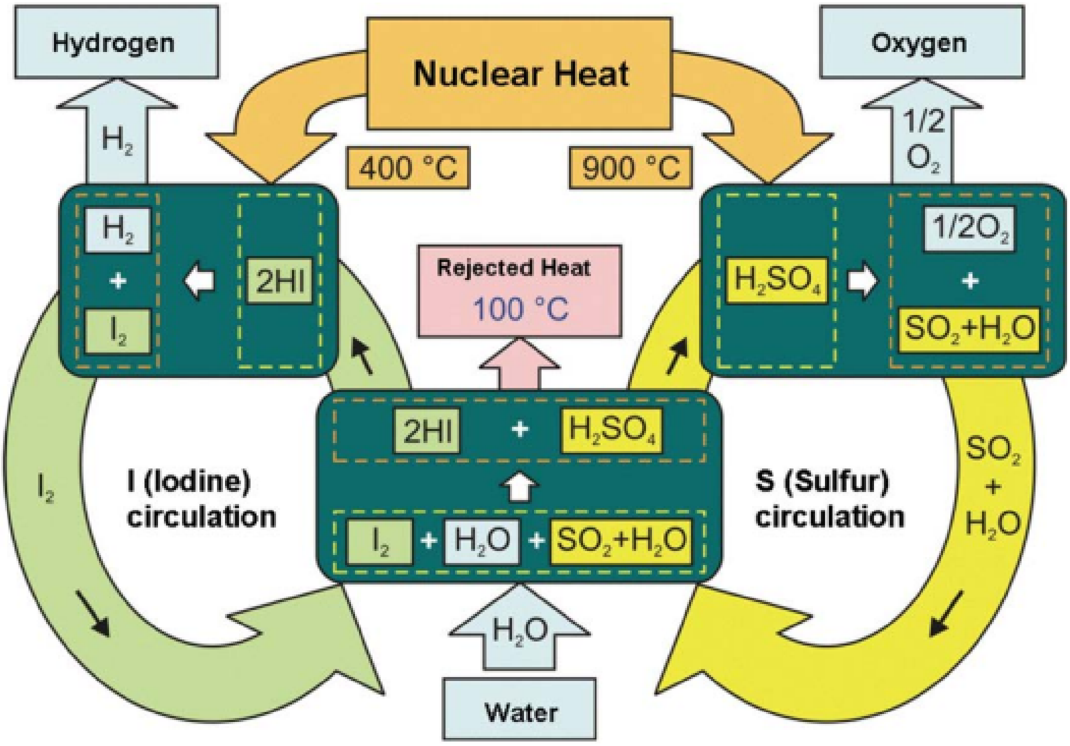


Figure 2.2: Schematic of the sulphur-iodine thermochemical water splitting cycle [13].

2.2 Process Energy Requirements

One of the main advantages of coupling a nuclear plant with hydrogen production lies in the reduction of electricity demand. In traditional electrolysis, the total energy required to break the water molecule must be supplied in the form of electricity, which is expensive.

In contrast, during HTSE, the water is already in the form of steam. The total demand for electricity is therefore reduced because the energy required to evaporate the water is supplied much more economically, since the direct heat output from the reactor is used.

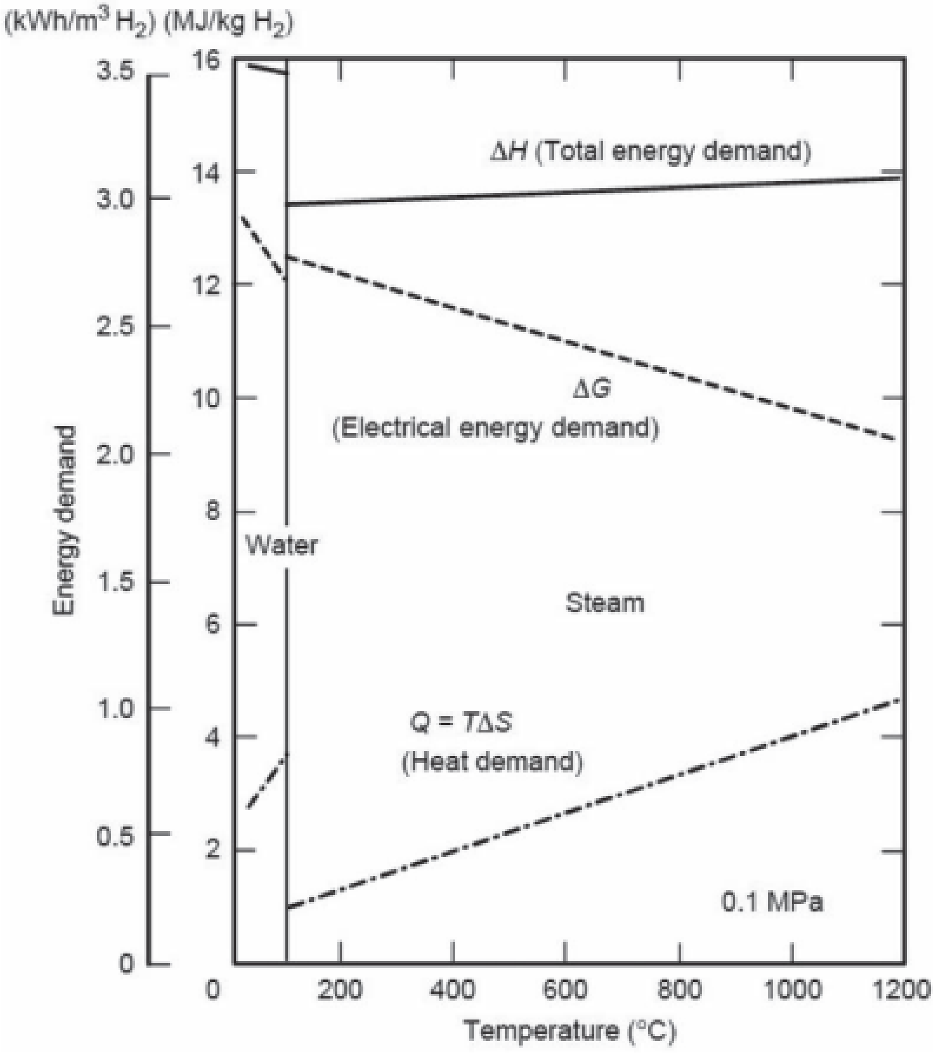


Figure 2.3: Energy demand for water/steam electrolysis as a function of temperature [13].

As the operating temperature increases, the demand for electricity decreases proportionally. Between 800 and 1000 °C, the electricity required is approximately 35% less than for standard electrolysis [13]. As a result, the overall thermodynamic efficiency (heat-to-hydrogen) increases significantly: HTSE systems can achieve efficiencies of 35% to 45% at 800 °C, reaching up to 50% at 900 °C. Even in the case of thermochemical cycles, there are high theoretical efficiencies, but these depend on how much heat can be recovered from the plant without dispersing it.

2.3 Reactor-Process Coupling (IHX)

Connecting a nuclear plant to a chemical plant requires extreme levels of safety. In this integration, the most critical component is the intermediate heat exchanger (IHX), which creates a secondary helium circuit located between the primary circuit and the chemical plant.

Using an intermediate circuit (IHX) is essential because [13]:

1. It physically separates the nuclear island from the chemical plant, protecting the reactor from any damage to the plant, such as explosions or fires.
2. It prevents the hydrogen produced from becoming radioactive, as it is physically separated from the radioactive elements in the reactor.
3. It prevents corrosive fluids, such as sulfuric acid, from the chemical plant from coming into contact with the reactor core.

Having a heat exchanger has a single thermodynamic disadvantage: a decrease in temperature, which results in a reduction in the heat available for chemical reactions.

There are two possible designs for constructing a heat exchanger (IHX). The traditional "tube bundle" design offers thick walls and very high corrosion resistance on the one hand, but is enormous in size on the other. Alternatively, to maximize efficiency and reduce size, modern research is focusing on Printed Circuit Heat Exchangers (PCHX). These compact modules are made by etching (with chemical acids) micro-channels into metal plates, which are then pressed and diffusion-welded together. PCHXs can withstand extremely high pressures (up to 50 MPa) and temperatures of up to 900 °C in a confined space, making them the most suitable engineering choice [13].

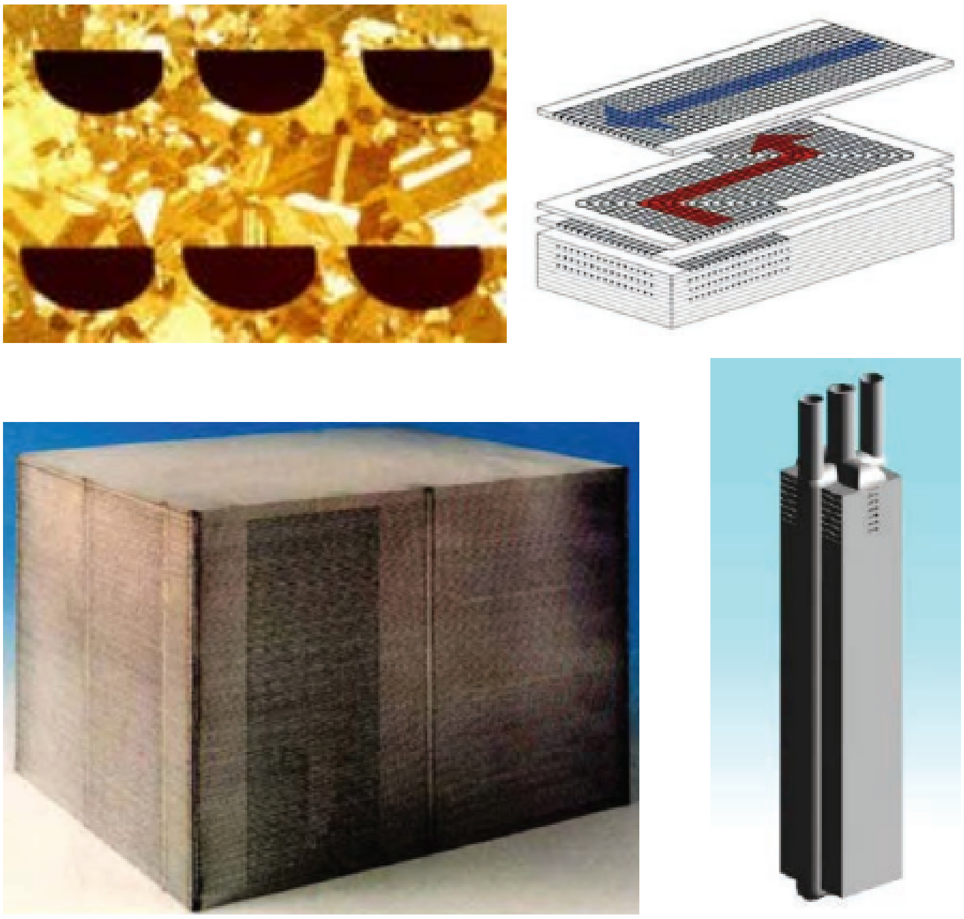


Figure 2.4: Internal structure of a Printed Circuit Heat Exchanger (PCHX) [13].

2.4 Impact of Outlet Temperature on Efficiency

The thermal efficiency of any method for producing hydrogen is based on the absolute laws of thermodynamics (the Carnot limit). Since breaking water requires chain reactions, a high heat source temperature is necessary to minimize thermodynamic losses.

This fundamental principle is mathematically described by the Carnot limit equation:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \tag{2.1}$$

where T_H is the absolute temperature of the nuclear heat source and T_L is the absolute temperature of the cold sink.

This strict dependence on temperature makes the Very High-Temperature Reactor (VHTR) the perfect Generation IV nuclear reactor for this purpose. The VHTR is cooled by helium gas and moderated by graphite, and is designed to be very safe thanks to passive safety systems. One of the advantages of this reactor is the high outlet temperature of the coolant, i.e., helium, which reaches temperatures between 900 and 1000 °C.

Operating at these temperatures drastically changes the economics of the plant. Studies show that at 900 °C, both High Temperature Steam Electrolysis (HTSE) and thermochemical cycles (S-I) exceed 50% total efficiency [13].

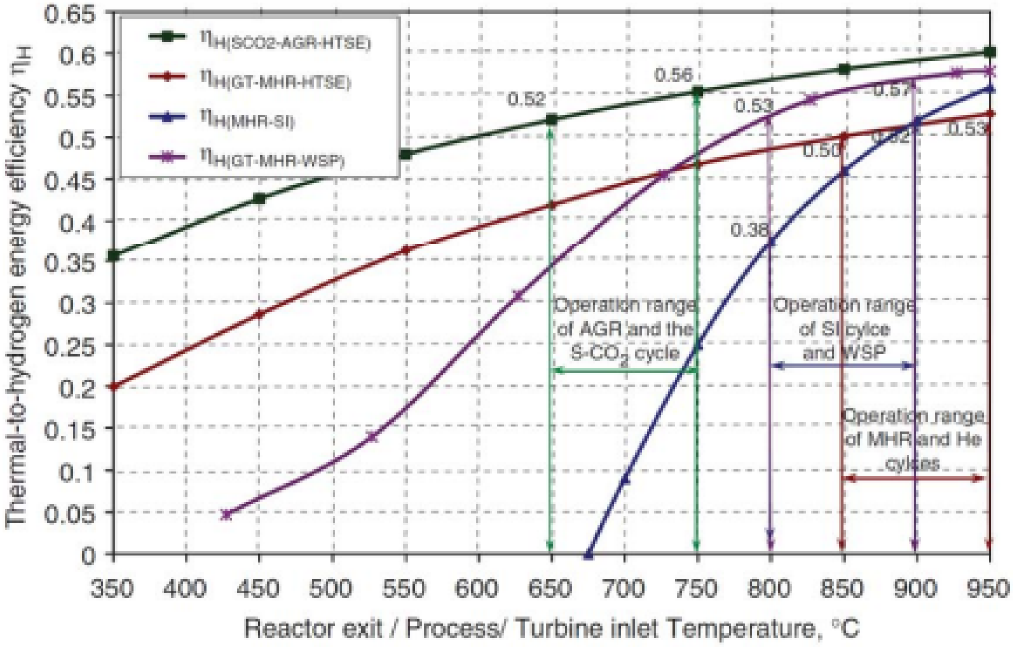


Figure 2.5: Thermal efficiencies for hydrogen production with HTSE and S-I cycle [13].

However, the two methods react differently when the temperature drops:

- In thermochemical cycles, if the reactor drops below 800 °C, efficiency plummets because there is not enough heat to evaporate the sulfuric acid, forcing the pumps to work extremely hard to circulate more liquids.
- In electrolysis (HTSE), on the other hand, efficiency is more stable even at lower temperatures (around 750 °C), ensuring a more flexible and easier-to-manage plant.

Finally, having a reactor at 1000 °C allows for “cogeneration”: a large gas turbine can be connected directly to the circuit to produce both hydrogen and electricity simultaneously, making the project economically viable for industry.

Considered Nuclear Technologies

As demonstrated in the previous chapter, thermodynamic efficiency is a fundamental parameter for hydrogen production (both through high-temperature electrolysis and thermochemical cycles) and is closely linked to the temperature of the process heat supplied by the reactor. Consequently, the choice of nuclear reactor to be coupled with the chemical plant becomes the determining factor for the technical and economic feasibility study of the overall system. This chapter addresses the different nuclear technologies considered for hydrogen production, analyzing their operating characteristics, thermodynamic limitations, and potential. The analysis will start with the most mature technologies currently available, which are characterized by lower operating temperatures than fourth-generation reactors. Light water reactors (LWRs), including promising small modular variants (SMR-LWRs), and heavy water reactors such as the CANDU reactor will be examined. Subsequently, some types of fourth-generation reactors will be analyzed, such as advanced gas-cooled technologies, specifically designed to achieve the high temperatures required to maximize hydrogen yield: HTGR reactors and their evolution, and VHTRs. Particular focus will be given to Japan's High Temperature Engineering Test Reactor (HTTR), a key test facility that has already demonstrated the practical feasibility of these architectures. Finally, the chapter concludes with a comparative assessment of the technological maturity of each reactor and its real applicability to the various chemical processes described above, outlining the future prospects for the industry.

3.1 LWR / SMR-LWR

The most widespread technology in the world at a commercial level is represented by Light Water Reactors (LWR). These plants, characterized by very high electrical power outputs (often exceeding 1000 MWe), use ordinary water as both the neutron moderator and the coolant fluid. The fuel employed is enriched uranium (with a U-235 isotope percentage typically between 3% and 5%), which is sintered into small cylindrical pellets of uranium dioxide (UO_2). These pellets are stacked inside long zirconium alloy tubes, forming fuel rods, which are in turn grouped into fuel assemblies. The chain reaction is regulated by the insertion or extraction of control rods (made of neutron-absorbing materials, such as boron or cadmium) directly among the fuel assemblies.

Based on the thermodynamic cycle of the plant, LWRs are divided into two main categories: Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR).

In **PWRs**, the core is located inside a huge steel pressure vessel that typically measures 12-13 meters in height and 5 meters in internal diameter, with a core volume of approximately 33 m^3 [14]. The heat generated by fission is removed by the water of a closed primary circuit, which is kept at very high pressures (about 15.5 MPa) to prevent boiling. This water reaches reactor outlet temperatures of about 324 °C and is sent to large heat exchangers, called steam generators. Here, the heat is transferred to a completely independent secondary circuit, filled with other water at a lower pressure; it is the water of this second circuit that boils, generating the steam that will drive the turbine connected to the alternator to produce electrical energy.

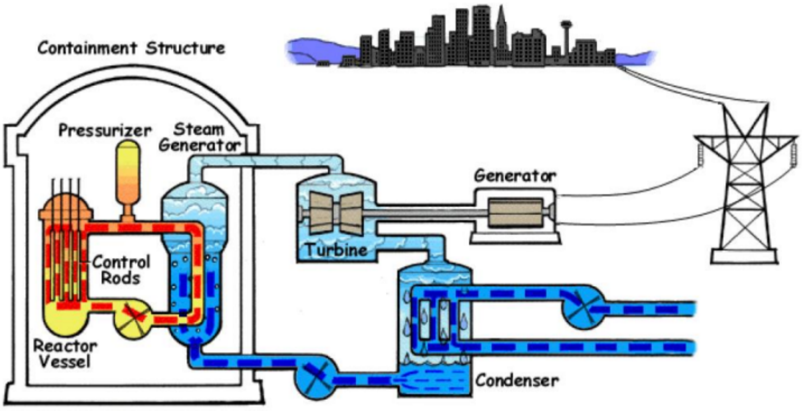


Figure 3.1: Schematic representation of a Pressurized Water Reactor (PWR) and its primary/secondary circuits [14].

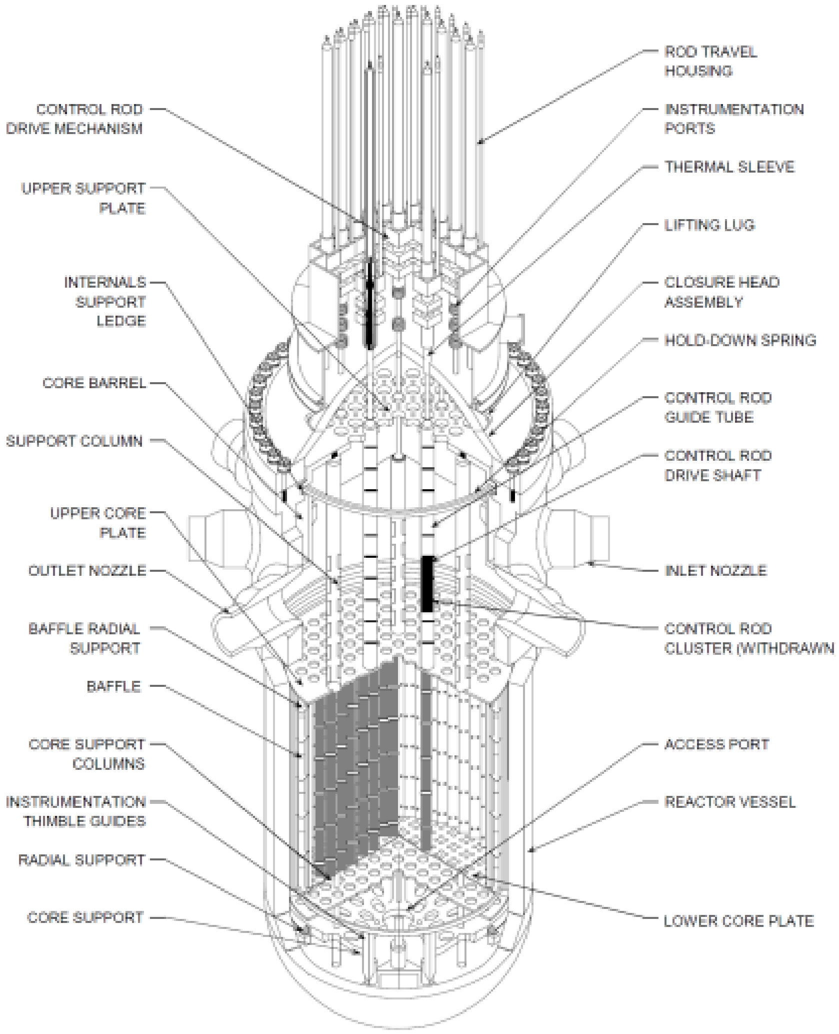


Figure 3.2: Detailed view of the PWR core and vessel components [14].

BWRs feature even more massive vessels, which can exceed 22 meters in height and 6 meters in diameter, housing cores with a volume of about 64 m^3 [14]. These reactors operate at significantly lower pressures (about 7.17 MPa). This allows the water to boil directly inside the reactor core, absorbing heat from the fuel rods. The steam thus produced reaches temperatures of about 288 °C at the vessel outlet and is sent directly to the turbine to generate electricity, eliminating the need for steam generators. In BWRs, due to the presence of steam and moisture separators in the upper part of the vessel, the control rods are inserted from the bottom upwards.

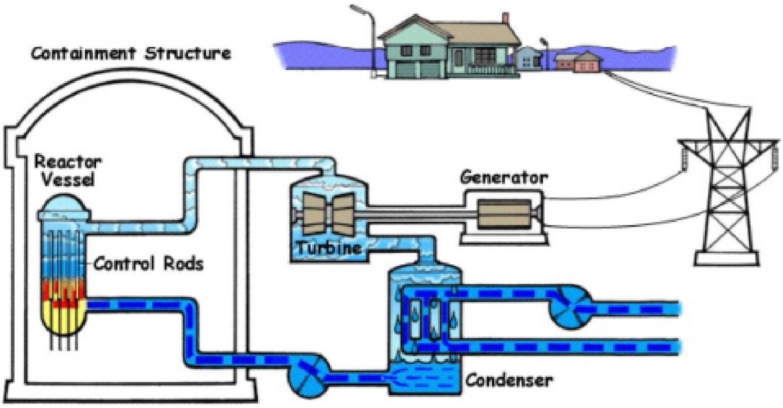


Figure 3.3: Schematic representation of a Boiling Water Reactor (BWR) direct cycle [14].

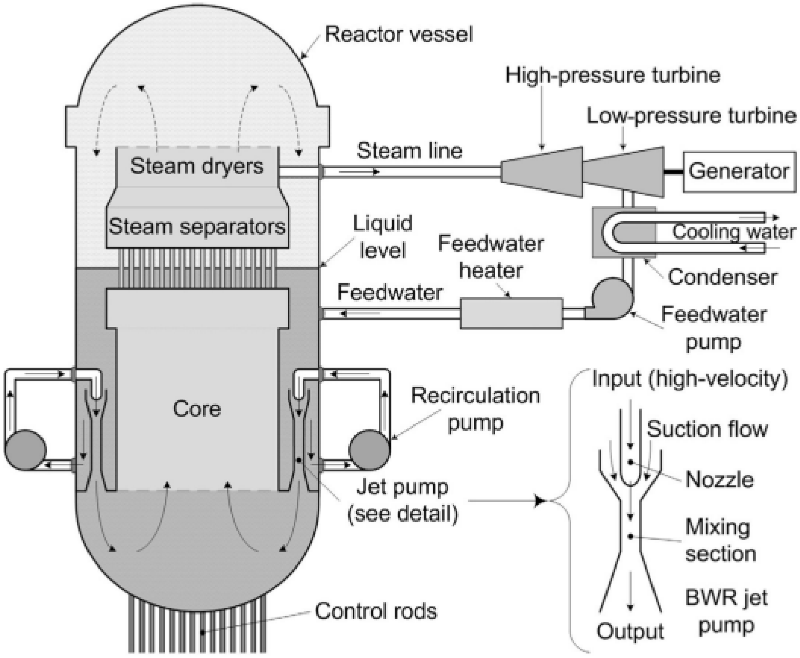


Figure 3.4: Detailed view of the BWR core, vessel, and moisture separation components [14].

To overcome the limitations related to the high costs and huge footprint of these giant plants, light water technology has recently been adapted for the development of Small Modular Reactors (SMR). SMRs have a reduced electrical power output (maximum 300 MWe) and extremely compact dimensions: the entire reactor module is small enough to be entirely mass-produced in an industrial facility. In addition to the size advantage, SMRs are equipped with advanced passive safety systems, which exploit physical principles such as natural circulation to cool the core in an emergency without the need for pumps. Among the most advanced designs are:

- **NuScale:** an "integral" PWR where the core and steam generators are enclosed in a single small vessel only 17.7 meters high and 2.7 meters wide, with an outlet temperature of 316 °C [15].

- **BWRX-300:** a simplified natural circulation BWR whose vessel has a reduced diameter of only 4 meters, with an outlet temperature of 288 °C [15].

However, due to their modest operating temperatures, the use of LWRs and SMR-LWRs for hydrogen production is strictly limited to the electrical supply of conventional cold water electrolyzers, precluding the use of thermochemical cycles unless external heat sources are integrated.

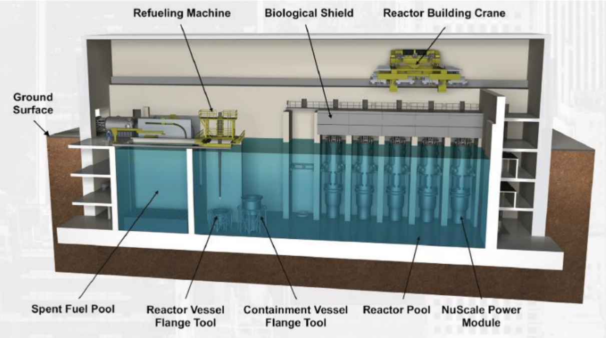


Figure 3.5: Schematic representation of the NuScale SMR plant [15].

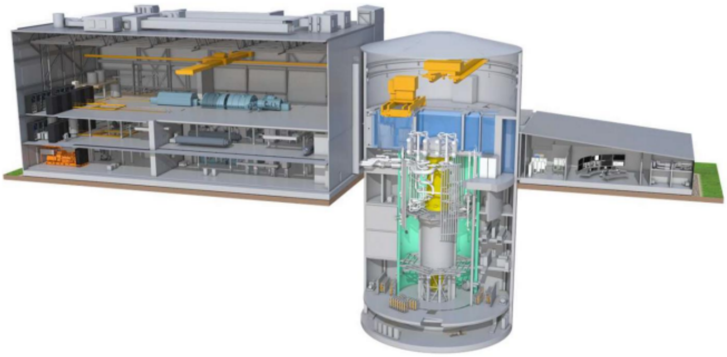


Figure 3.6: Schematic representation of the BWRX-300 SMR plant [15].

3.2 CANDU

The CANDU (CANada Deuterium Uranium) reactor delivers medium-high electrical power (between 600 and 900 MWe) and differs from LWRs in that it uses heavy water (D_2O) both as a neutron moderator and as a coolant. In fact, it belongs to the family of pressurized heavy water reactors (PHWR).

Since deuterium has a low neutron absorption capacity, the fuel does not require enrichment processes: natural uranium (containing just 0.7% of the U-235 isotope) is used, sintered into UO_2 pellets, and inserted into zirconium alloy tubes to form fuel bundles just half a meter long. However, the use of natural uranium requires much more space to slow down the neutrons; for this reason, a CANDU reactor has a core with a volume of approximately 400 m^3 [16].

The structural design is also different: instead of a single pressure vessel, a horizontal low-pressure cylindrical tank called a *calandria* is used. The calandria is filled with cold heavy water, which acts as a moderator, and is traversed by hundreds of horizontal "pressure tubes". The short fuel bundles are loaded into these tubes. This design allows the fuel to be continuously reloaded without having to shut down the plant. The chain reaction is regulated by control rods that are inserted vertically from above directly into the low-pressure moderator of the calandria.

The operation involves removing the heat from fission by pumping high-pressure heavy water into the horizontal tubes containing the fuel. The coolant enters the core at 267 °C and exits at approximately 310 °C; the pressure is maintained at approximately 10 MPa (lower than that of a PWR but sufficient to keep the heavy water in a liquid state without boiling it) [16]. The hot heavy water leaves the reactor and is conveyed to the steam generators, where it transfers its heat to an independent secondary circuit filled with light water. The fluid in the secondary circuit, being at a lower pressure (approximately 4.7 MPa), boils at approximately 260 °C, generating steam that will drive the turbine to subsequently produce electricity.

Due to the structural limitations of the pressure pipes and the intrinsic properties of heavy water, the temperatures in this plant cannot be increased further. As a result, the overall thermodynamic efficiency of the cycle is around 28-30%. As with light water reactors, these outlet temperatures (310 °C) are too low to allow direct coupling of the reactor with advanced chemical processes, limiting the use of CANDU for hydrogen production to the supply of electricity for conventional cold electrolysis.

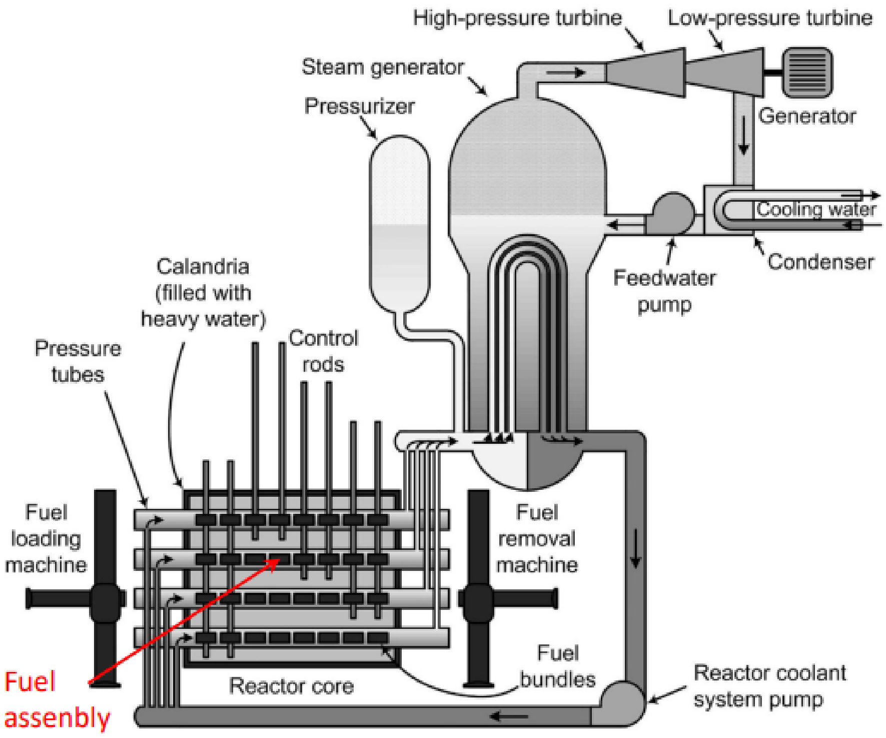


Figure 3.7: Schematic representation of a CANDU reactor, showing the calandria and the horizontal pressure tubes [16].

3.3 HTGR

High Temperature Gas-cooled Reactors (HTGR) were designed to overcome the thermodynamic limits of water-cooled reactors. These plants use helium gas as the coolant fluid and graphite as the neutron moderator. The choice of helium is necessary for high-temperature applications: it is a chemically much more inert gas compared to carbon dioxide, it does not absorb thermal neutrons, and it does not become radioactive when passing through the core [17].

The fuel is a micro-ceramic known as TRISO (TRI-structural ISOtropic). Unlike the classic macroscopic pellets used in LWRs, HTGR fuel consists of small spherical particles of highly enriched uranium-235, with a diameter of 100-300 μm. Each sphere is enclosed in a multi-layered protective shell of carbon and ceramic (often between 50 and 300 μm). The TRISO coating includes a porous inner layer of pyrolytic carbon (the porosity is 20%, specifically designed to absorb fission gases), an intermediate layer of dense pyrolytic carbon, and an outer shell of silicon carbide. The fuel reaches 1300 °C during normal steady-state operation and can withstand peaks up to 1600 °C during high-power transients without melting, effectively trapping all radioactive fission products [17].

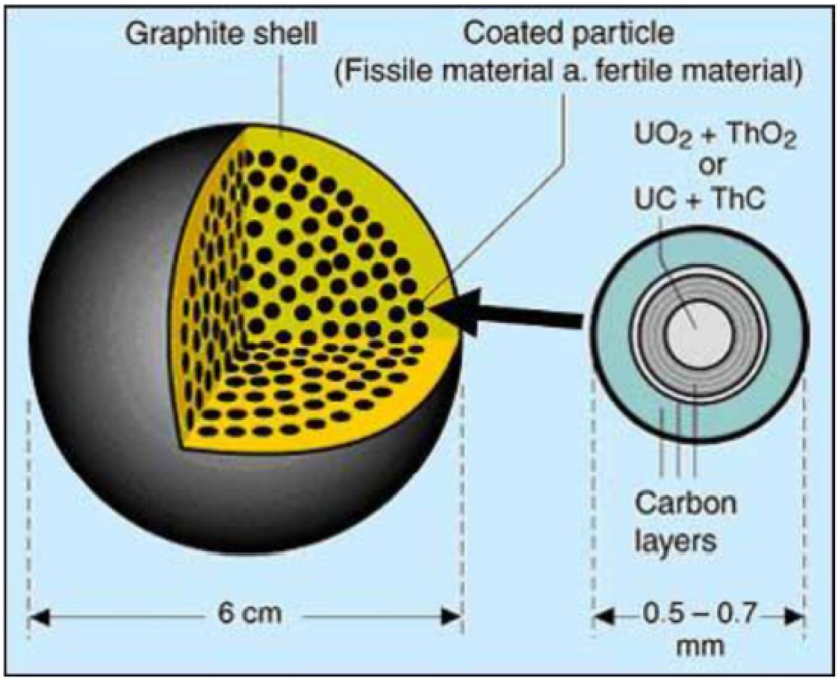


Figure 3.8: Schematic representation of TRISO fuel[17].

Depending on the reactor design, the TRISO micro-particles are embedded in a graphite matrix to form the macroscopic fuel in two main variants:

- **Prismatic block reactors:** the fuel is inserted inside large hexagonal graphite blocks, which are traversed by vertical channels for the insertion of fuel elements and the passage of the coolant.
- **Pebble Bed Reactors (PBR):** the fuel is shaped into graphite spheres that fill the core cavity. In this configuration, the helium gas moves transversally from one element to another without encountering structural obstacles.

From a thermo-hydraulic point of view, HTGRs require massive structures, with a core reaching a volume of about 354 m^3 [18]. The cooling system is composed of various loops, housed inside a large pre-stressed concrete cylinder. In modular designs (MHTGR), the helium flow is pushed downwards through the core by main circulators; the gas enters at about 450 °C and reaches extremely high core outlet temperatures, ranging between 700 °C and 1000 °C (with reference designs typically operating at 780 °C) [18]. The hot gas is then channeled towards helical coil steam generators, a different solution compared to the U-tube generators typical of LWRs.

A crucial advantage of HTGRs is their inherent safety. The combination of the extreme resistance of the TRISO fuel and the enormous heat capacity of the graphite moderator ensures that, even in the event that a severe accident causes the total loss of the cooling system, the core cannot melt, thus avoiding any release of radioactive material into the environment [17].

Finally, the core outlet temperatures guarantee a highly efficient power generation cycle, with a thermal efficiency that approaches 48%. More importantly, this high-quality heat unlocks the potential for direct application in industrial processes (such as oil refining and ammonia production), making the HTGR the ideal candidate to power thermochemical cycles and High-Temperature Steam Electrolysis (HTSE) for massive, zero-emission hydrogen production.

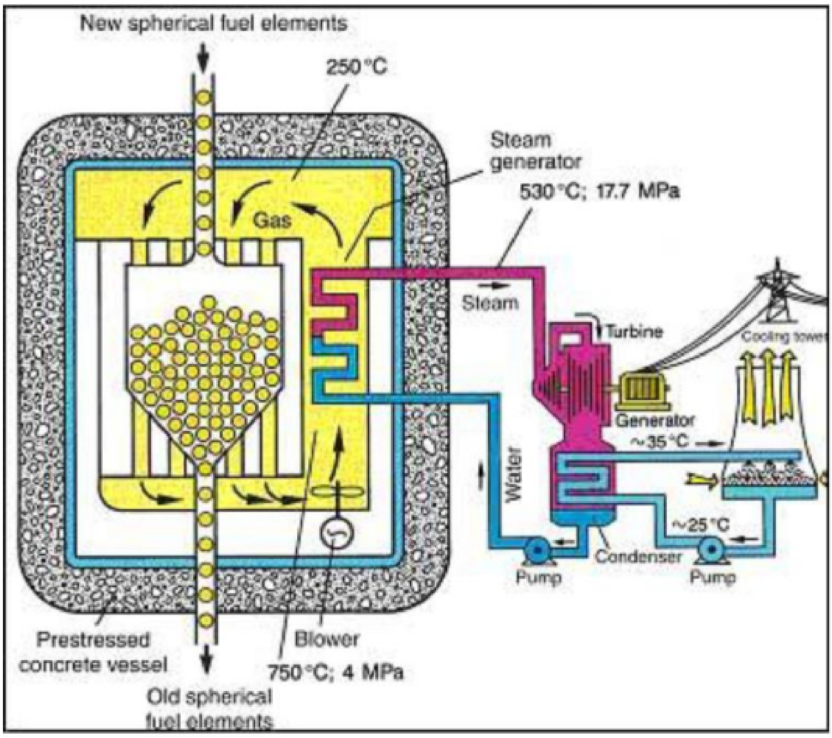


Figure 3.9: Schematic representation of an HTGR plant overview [17].

3.4 VHTR

The Very High Temperature Reactor (VHTR) represents the technological evolution of traditional HTGRs and has been selected by the Generation IV International Forum (GIF) as one of the six Generation IV nuclear systems. The primary objective of this technology is not only the highly efficient production of electrical energy, but also the supply of process heat for energy-intensive industrial applications, primarily the massive production of hydrogen.

The VHTR, belonging to the HTGR family, uses helium gas as the coolant fluid, a graphite moderator (in a prismatic block or pebble bed configuration), and TRISO fuel. The main difference lies in the operating temperatures: thanks to the development of new advanced structural materials, the VHTR is designed to reach core coolant outlet temperatures above 900°C, with the theoretical goal of reaching up to 1000°C [19].

At these thermal levels, the reactor can be coupled directly and with very high efficiency to both High-Temperature Steam Electrolysis (HTSE) and thermochemical cycles for water splitting, such as the Sulfur-Iodine (S-I) cycle, without the need to integrate external heat sources [19].

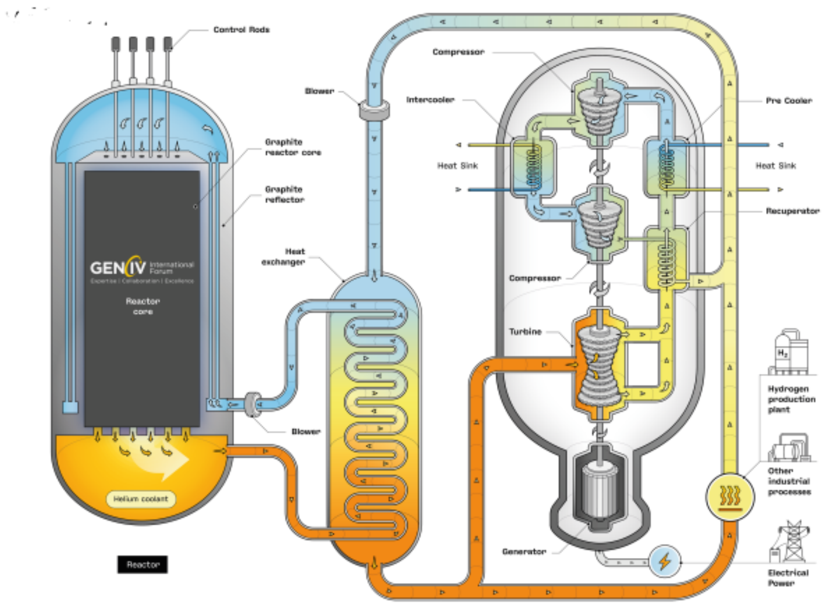


Figure 3.10: Schematic representation of the Very High Temperature Reactor (VHTR) [20].

3.5 HTTR

The High Temperature Engineering Test Reactor, HTTR, is a Japanase experimental reactor of 30 MWth, operated by the Japan Atomic Energy Agency (JAEA). Its construction represents a milestone in the practical demonstration of the capabilities of gas-cooled reactors.

The HTTR core is of the prismatic type, consisting of hexagonal graphite blocks that house the TRISO fuel. According to data reported by the IAEA, the hallmark of this plant is its thermal capacity: the HTTR was the first nuclear reactor in the world to successfully reach a helium gas outlet temperature of 950°C, maintaining stable and safe operating conditions [19].

The generated heat is extracted through a primary circuit and transferred to a secondary circuit via an Intermediate Heat Exchanger (IHX). This configuration has made it possible to concretely test the extraction of ultra-high-temperature heat for industrial uses. Currently, the HTTR is the primary worldwide testbed to demonstrate the feasibility of coupling a nuclear reactor with a pilot plant for hydrogen production via the Sulfur-Iodine thermochemical cycle [19].

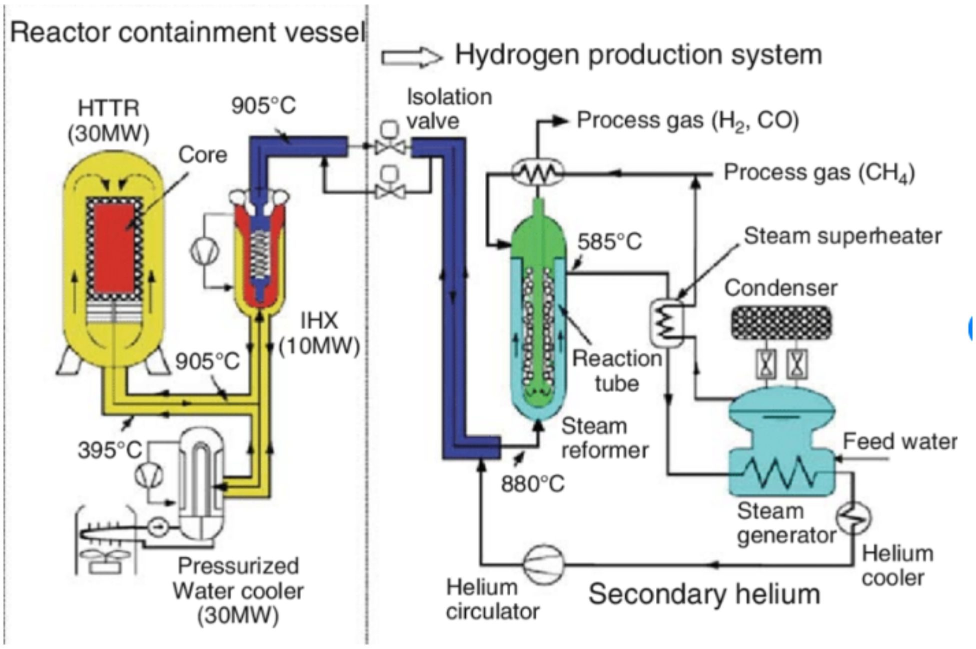


Figure 3.11: Schematic diagram of the HTTR coupled with a hydrogen production plant [21].

3.6 Technological Maturity and Process Applicability

The choice of the type of nuclear plant for hydrogen production is based on a compromise between the technological maturity of the former and the operating temperatures required by the chemical plant.

On the one hand, Light Water Reactors (LWR) and heavy water reactors (CANDU) enjoy excellent technological maturity, being widely used and reliable technologies worldwide. However, they feature very low reactor outlet temperatures for certain processes, which limits their applicability exclusively to powering conventional low-temperature electrolyzers, such as alkaline or PEM systems. Water-cooled Small Modular Reactors (SMR) also fall into this category: while offering advantages in terms of flexibility, design, and passive safety, they present the same thermodynamic constraints. In this configuration, the reactor provides solely the electrical energy required for the process, without being able to exploit the thermal potential to improve the overall efficiency of water splitting.

On the other hand, high-efficiency processes for hydrogen production, such as High-Temperature Steam Electrolysis (HTSE) and thermochemical cycles (such as the Sulfur-Iodine cycle), require a large amount of heat, with temperatures ranging between 700 °C and 1000 °C. These parameters, therefore, favor the use of gas-cooled reactors (HTGR and VHTR). Although experimental plants like the HTTR have successfully demonstrated the thermodynamic and operational feasibility of these temperatures, gas technology is still in a demonstration phase and has not yet reached the large-scale commercial deployment typical of LWRs.

In summary, the aforementioned reactors can be used for hydrogen production, but they differ based on the objective: while the short-term approach for nuclear hydrogen relies on coupling conventional water reactors with cold electrolysis, the long-term, higher-efficiency prospect lies in the commercial development of HTGR and VHTR reactors. The latter are indeed the only systems capable of powering thermochemical water splitting processes in an economically and thermodynamically advantageous manner, by directly coupling the nuclear heat to the chemical plant.

Hydrogen Production Technologies

4.1 Thermodynamics of Water Splitting

Hydrogen production can be initiated through the endothermic process of water splitting. Macroscopically, the overall reaction describing this process is expressed as follows:

$$\mathrm{H_2O}_{(l,g)} \rightarrow \mathrm{H}_{2(g)} + \frac{1}{2}\mathrm{O}_{2(g)} \tag{4.1}$$

The splitting of the water molecule requires a specific amount of energy to break its covalent bonds. Thermodynamically, the total energy required for this process is quantified by the enthalpy change of the system (ΔH). This energy requirement is described by the following fundamental equation:

$$\Delta H = \Delta G + T\Delta S \tag{4.2}$$

It represents the sum of two essential components: the Gibbs Free Energy (ΔG), representing the electrical/mechanical work, and the thermal energy, defined by the product of absolute temperature and entropy change ($T\Delta S$) [19].

Utilization of Nuclear Energy

At ambient temperature (25°C and 1 atm), water splitting requires an enthalpy change (ΔH) of 285.8 kJ/mol. Under these conditions, the thermal energy ($T\Delta S$) that can be absorbed from the environment is only 48.7 kJ/mol. This means that the remaining energy, equal to 237.1 kJ/mol (ΔG), must be supplied externally as electricity.

However, as the operating temperature of the system increases, the entropy change (ΔS) grows, causing the $T\Delta S$ term to become progressively larger. Consequently, the share of required electrical energy decreases. By continuing to raise the temperature (for example, in the case of HTSE), the electrical energy demand drops by up to 30-40%. The key parameters for calculating a plant's production efficiency refer to the Lower Heating Value (LHV) or Higher Heating Value (HHV) of the produced hydrogen compared to the total electrical and thermal energy input ($\eta = Energy_{out}/Energy_{in}$). For this reason, utilizing nuclear energy—through the direct use of process heat or generated electricity—can radically optimize hydrogen production [19].

4.2 Proton Exchange Membrane (PEM) Electrolysis

PEM (Proton Exchange Membrane) electrolysis is a low-temperature water splitting technology distinguished by its high power density, compact design, and operational flexibility [4].

Operating Principle and Electrochemical Reactions

PEM cells use a solid polymer electrolyte. Liquid water is pumped into the anode compartment of the cell. Here, by applying a potential difference, the water is oxidized and split into gaseous oxygen (O_2), protons (H^+ ions), and electrons (e^-).

$$\text{Anode Reaction: } \mathrm{H_2O} \rightarrow \frac{1}{2}\mathrm{O_2} + 2\mathrm{H^+} + 2\mathrm{e^-} \tag{4.3}$$

$$\text{Cathode Reaction: } 2\mathrm{H^+} + 2\mathrm{e^-} \rightarrow \mathrm{H_2} \tag{4.4}$$

An oxidation reaction occurs at the anode, while a reduction reaction takes place at the cathode. The electrons travel through the external electrical circuit (as they cannot pass through the membrane), providing the required work ΔG. Simultaneously, the H^+ protons cross the solid membrane—which is permeable only to cations—reaching the cathode. In the cathode area, the protons recombine with the electrons from the external circuit, reducing to form ultra-high-purity gaseous hydrogen.

Materials and Operating Parameters

The internal environment of a PEM cell is highly acidic and subjected to severe oxidative stress at the anode. To prevent the instantaneous degradation of the components, a solid membrane made of perfluorosulfonic acid (PFSA), commercially known as Nafion, is utilized. Similarly, the bipolar plates must resist corrosion; hence, they are constructed from titanium, often coated with platinum or gold to minimize contact resistance. Furthermore, the catalysts require Platinum Group Metals (PGM): Platinum (Pt) on carbon for the cathode, and Iridium or Ruthenium (e.g., IrO_2) for the anode. The use of noble materials like PGMs significantly increases the initial Capital Expenditure (CAPEX) [22].

Operationally, the plant works at temperatures between 50°C and 80°C. The main advantage is its ability to generate pre-compressed hydrogen directly within the cell, ranging from 30 to 70 bar, thus saving on downstream compressor costs. Current densities are extremely high, typically between 1.0 and 2.0 A/cm^2.

Nuclear Coupling (SMR-LWR)

Since this process occurs at temperatures around 80°C, PEM technology can be seamlessly coupled with light water Small Modular Reactors (SMR-LWRs), which do not produce high-temperature process heat but provide reliable electrical energy. Approximately 50-55 kWh are consumed for each kilogram of hydrogen produced. Another major advantage of PEM is its rapid dynamic response, capable of varying from 0% to 160% of its nominal load in milliseconds. This allows the PEM electrolyzer to instantaneously absorb excess nuclear energy peaks to produce hydrogen (Peak Shaving), optimizing the combined plant's economics.

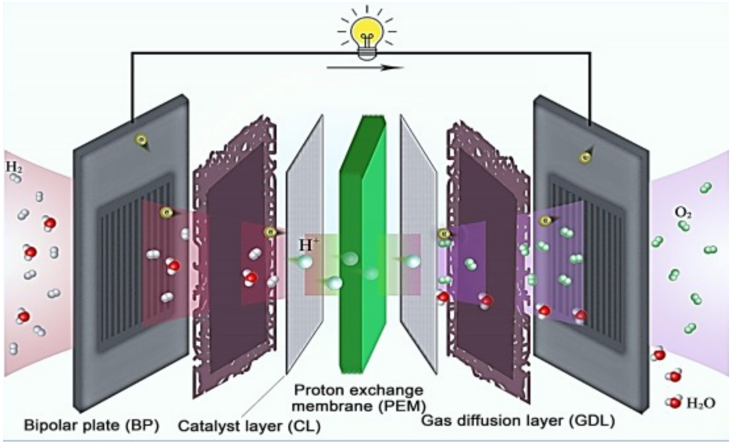


Figure 4.1: Schematic principle of Proton Exchange Membrane (PEM) water electrolysis [22].

4.3 Alkaline Water Electrolysis (AWE)

For nearly a century, Alkaline Water Electrolysis (AWE) has been the most mature and widely deployed green/pink hydrogen production technology at the industrial level. As a result, it guarantees low initial investment costs, high reliability, and an extended component lifespan [4].

Operating Principle and Electrochemical Reactions

Unlike PEM systems, AWE does not use solid membranes but rather a liquid electrolytic bath in which the electrodes are immersed. By applying direct current, water is reduced at the cathode, forming gaseous hydrogen and releasing hydroxide ions (OH^-).

$$\text{Cathode Reduction: } 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{4.5}$$

$$\text{Anode Oxidation: } 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \tag{4.6}$$

The OH^- ions migrate through the liquid electrolyte toward the anode under the influence of the electric field.Once they have reached the anode, they give their electrons, forming gaseous oxygen and recreating water molecules.

Materials and Operating Parameters

The liquid electrolyte is an aqueous solution of Potassium Hydroxide (KOH) or, more rarely, Sodium Hydroxide (NaOH). The advantage of an alkaline environment is its low corrosivity on standard metals, which avoids the use of expensive noble metals as seen in PEM systems. Electrodes are typically made of Nickel, and the structural frames are made of stainless steel. The anode and cathode compartments are separated by a thick porous diaphragm made of Zirfon, a matrix of zirconium oxide and polysulfone. The diaphragm is critical for system safety as it allows the passage of OH^- ions but physically blocks the H_2 and O_2 bubbles, preventing the formation of explosive gaseous mixtures. These systems operate at temperatures between 60°C and 90°C and pressures ranging from 1 to 30 bar. The specific energy consumption is similar to PEM, around 50-55 kWh/kg_{H_2}. However, due to the high ohmic resistance of the liquid electrolyte, current densities are much lower compared to PEM (between 0.2 and 0.4 A/cm^2), making the plants physically much bulkier for the same power output.

Nuclear Coupling (CANDU and Large LWRs)

This technology is well-suited for coupling with large-scale and highly stable reactors such as CANDU (PHWR) and traditional PWR/BWRs. A disadvantage of alkaline systems is their limited flexibility in managing load variations; significantly lowering the power can cause hydrogen to diffuse into the oxygen compartment (cross-over), posing a severe safety risk. Therefore, reactors like CANDUs, which typically operate in steady "baseload" mode (24/7 continuous production), are the most suitable for this technology, providing stable power to massive alkaline electrolyzer farms for industrial-scale production.

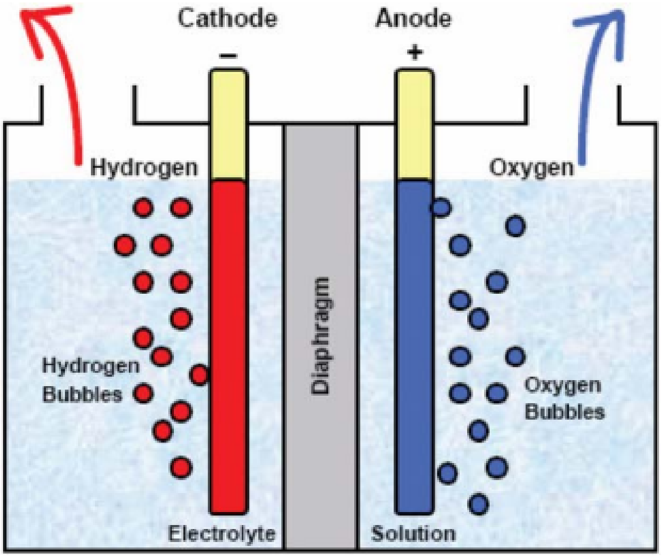


Figure 4.2: Schematic principle of alkaline water electrolysis [4].

4.4 Hybrid Thermochemical Cycles: The Copper-Chlorine (Cu-Cl) Cycle

One of the engineering challenges concerns pure thermochemical cycles, which require temperatures as high as 900°C. To address this, research has developed hybrid thermo-electrochemical cycles. A promising example for medium-temperature nuclear coupling is the Copper-Chlorine (Cu-Cl) cycle [19].

Operating Principles and Electrochemical Reactions

The Cu-Cl cycle splits water using two phases: a series of heat-driven chemical reactions and an electricity-driven electrolytic phase, utilizing recycled copper and chlorine compounds. The process is divided in:

- **Hydrolysis Reaction (Endothermic):** Copper (II) chloride reacts with steam at approximately 400°C to form copper oxychloride and gaseous hydrochloric acid.

$$\mathrm{2CuCl_2 + H_2O \rightarrow Cu_2OCl_2 + 2HCl} \tag{4.7}$$

- **Decomposition Reaction (Thermochemical):** Copper oxychloride, at around 500-530°C, releases pure oxygen and forms copper (I) chloride. This is the phase that requires nuclear process heat.

$$\mathrm{Cu_2OCl_2 \rightarrow 2CuCl + \frac{1}{2}O_2} \tag{4.8}$$

- **Electrochemical Phase:** Hydrochloric acid and copper (I) chloride react in a low-temperature electrolytic cell (about 100°C) using electrical energy, producing gaseous hydrogen and regenerating the initial copper (II) chloride.

$$2CuCl + 2HCl \rightarrow 2CuCl_2 + H_2 \tag{4.9}$$

Materials and Operating Parameters

Operating at maximum temperatures of around 530°C significantly reduces the corrosive stress of chlorine compounds on the main plant components compared to 900°C cycles. Alloys resistant to corrosion or glass-ceramic coatings are used to produce the chemical reactors and heat exchangers. Finally, the overall system efficiency is estimated to be around 43-45%.

Nuclear Coupling (CANDU and SCWR)

Its maximum temperature requirement of 530°C makes it the only advanced thermochemical cycle that can be coupled with evolutionary heavy water CANDU reactors (such as the Supercritical Water Reactor - SCWR) or liquid metal-cooled fast reactors, without necessarily waiting for the commercial-scale development of gas-cooled reactors (HTGRs).

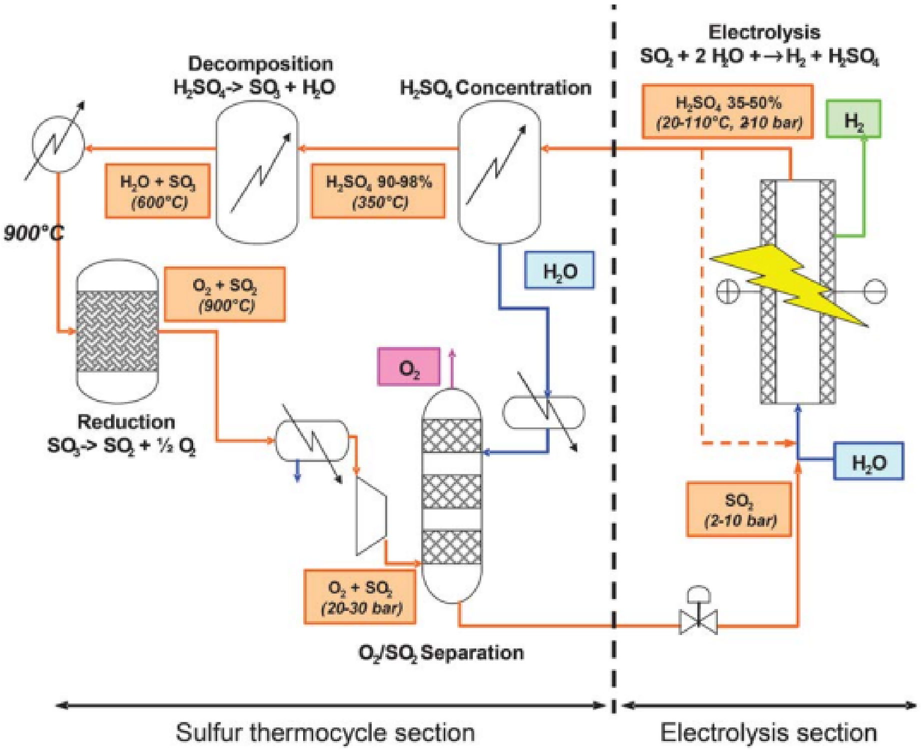


Figure 4.3: Block flow diagram of a hybrid thermo-electrochemical cycle [19].

4.5 High-Temperature Steam Electrolysis (HTSE / SOEC)

To overcome the efficiency limits of low-temperature electrolysis, nuclear research has shifted toward High-Temperature Steam Electrolysis (HTSE), based on Solid Oxide Electrolysis Cells (SOEC) [19].

Operating Principle and Electrochemical Reactions

SOECs do not split liquid water but superheated steam, instead of AWE and PEM. The steam is fed to the cathode, where it receives electrons and splits into gaseous hydrogen and oxygen ions (O^{2-}).

$$\text{Cathode Reaction: } H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{4.10}$$

The oxygen ions travel through the solid ceramic electrolyte (which is permeable only to anions at very high temperatures) until they reach the anode. Here, they yield their electrons, combining to form pure molecular oxygen.

$$\text{Anode Reaction: } O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \tag{4.11}$$

Materials and Operating Parameters

To allow the mobility of oxygen ions, the cell must operate at extreme temperatures (700°C - 850°C). The solid electrolyte is made of Yttria-Stabilized Zirconia (YSZ), an ion-conducting ceramic. The cathode is typically a cermet (ceramic-metal composite) of Nickel and YSZ, while the anode is made of mixed conducting perovskites (such as strontium-doped lanthanum manganite - LSM). The main limitation of this technology is the accelerated degradation of ceramic materials due to cyclic thermal stresses. Thanks to the supplied heat, the required electrical energy quota drops drastically (about 38 kWh/kg compared to 55 kWh/kg for PEM), bringing the overall plant efficiency close to 50%.

Nuclear Coupling (HTGR)

SOECs are the ideal technology for High-Temperature Gas-cooled Reactors (HTGRs). The heat from the primary helium gas (exiting at 750-850°C) is transferred via an Intermediate Heat Exchanger (IHX) to vaporize and superheat the water, while the reactor's alternator provides the remaining necessary electrical power.

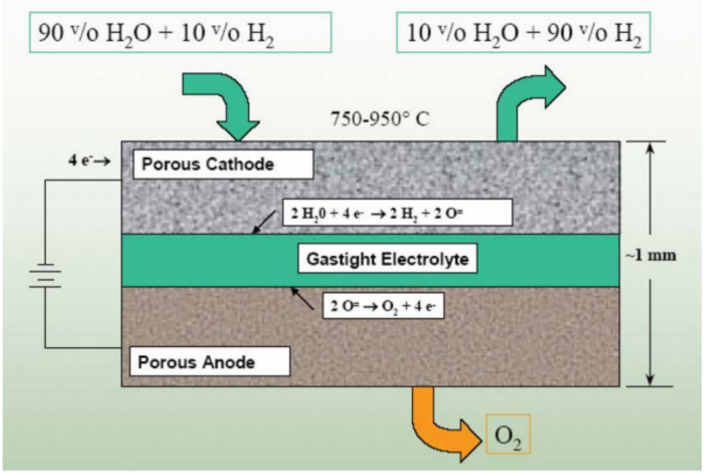


Figure 4.4: Schematic principle of a Solid Oxide Electrolysis Cell (SOEC) for high-temperature steam electrolysis [19].

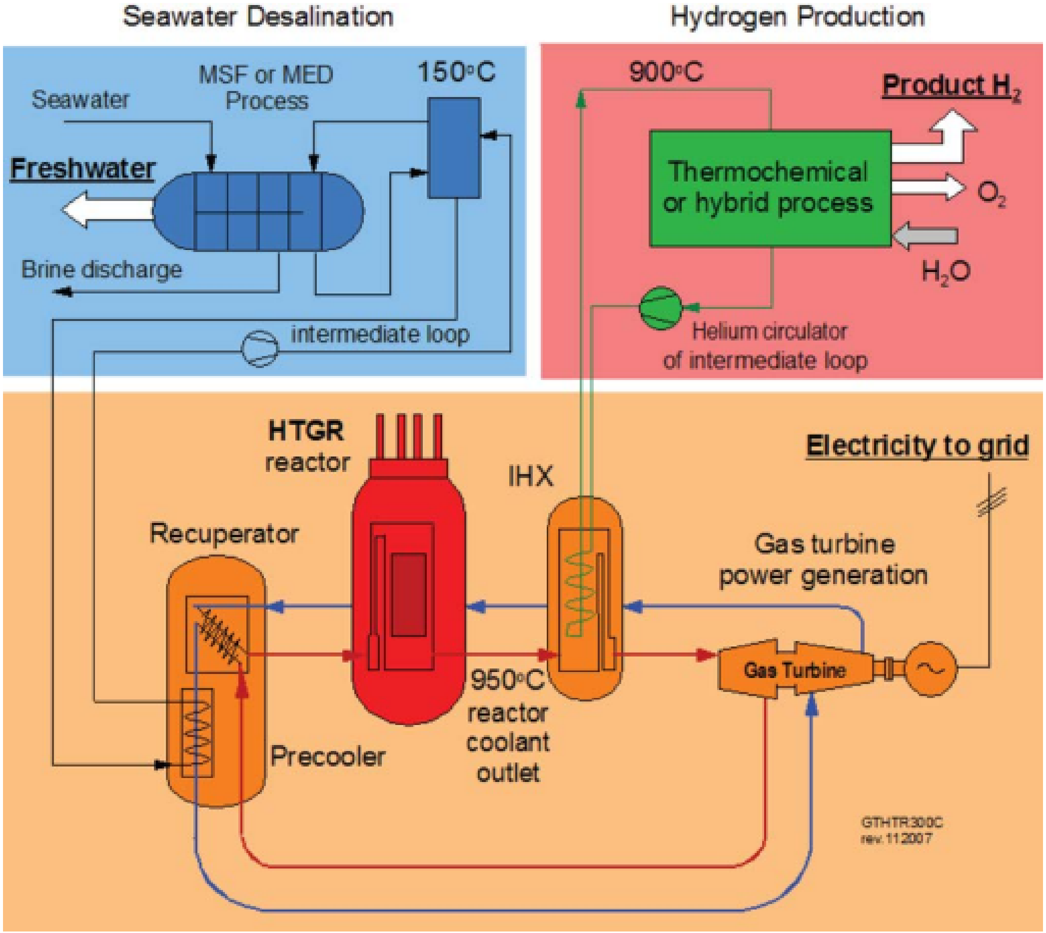


Figure 4.5: Schematic of an HTGR cogeneration plant for hydrogen production [19].

4.6 Pure Thermochemical Cycles: The Sulfur-Iodine (S-I) Cycle

Pure thermochemical cycles represent the technological frontier for massive water splitting because they almost entirely eliminate the need for electrical energy (required only for auxiliary systems and pumping), exclusively utilizing nuclear heat. The most globally studied and promising cycle is the Sulfur-Iodine (S-I) cycle [19].

Operating Principle and Chemical Reactions

The S-I cycle is a process divide in trhee steps in which all reactants (sulfur and iodine) are continuously regenerated and recycled within the plant.

- **Bunsen Reaction (Exothermic):** Water, sulfur dioxide, and iodine react to form two acids: sulfuric acid and hydroiodic acid. This reaction occurs at approximately 120°C.
$$I_2 + SO_2 + 2H_2O \to 2HI + H_2SO_4 \tag{4.12}$$
- **Sulfuric Acid Decomposition (Endothermic):** This is the reaction occurring at the highest temperature, around 850°C. Sulfuric acid is first vaporized and then decomposed to release oxygen and regenerate sulfur dioxide for the previous reaction.
$$H_2SO_4 \to H_2O + SO_2 + \frac{1}{2}O_2 \tag{4.13}$$
- **Hydroiodic Acid Decomposition (Endothermic):** Hydroiodic acid is decomposed at 450°C to release the produced hydrogen and regenerate the iodine needed for the first reaction.
$$2HI \to H_2 + I_2 \tag{4.14}$$

Materials, Parameters, and Nuclear Coupling (VHTR)

This process achieves a thermodynamic efficiency that can exceed 50% due to the absence of an electrolytic phase. However, there are significant technological limits regarding materials, which struggle to handle boiling sulfuric acid and hydroiodic acid. In this case, advanced materials like superalloys or Silicon Carbide (SiC) are required to withstand this type of stress. Since the process requires extremely high temperatures, the only reactor type capable of sustaining them is a VHTR (Very High Temperature Reactor) or HTTR prototypes, which feature very high core outlet temperatures, capable of transferring heat at 900°C-1000°C via secondary helium circuits.

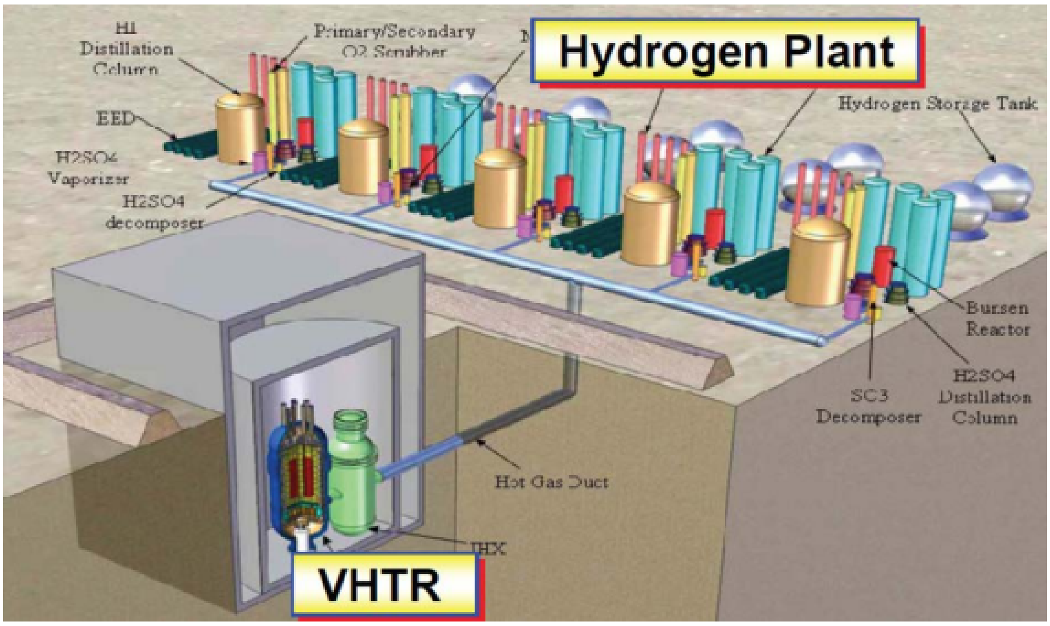


Figure 4.6: Schematic representation of a Very High Temperature Reactor (VHTR) coupled with a hydrogen production plant [19].

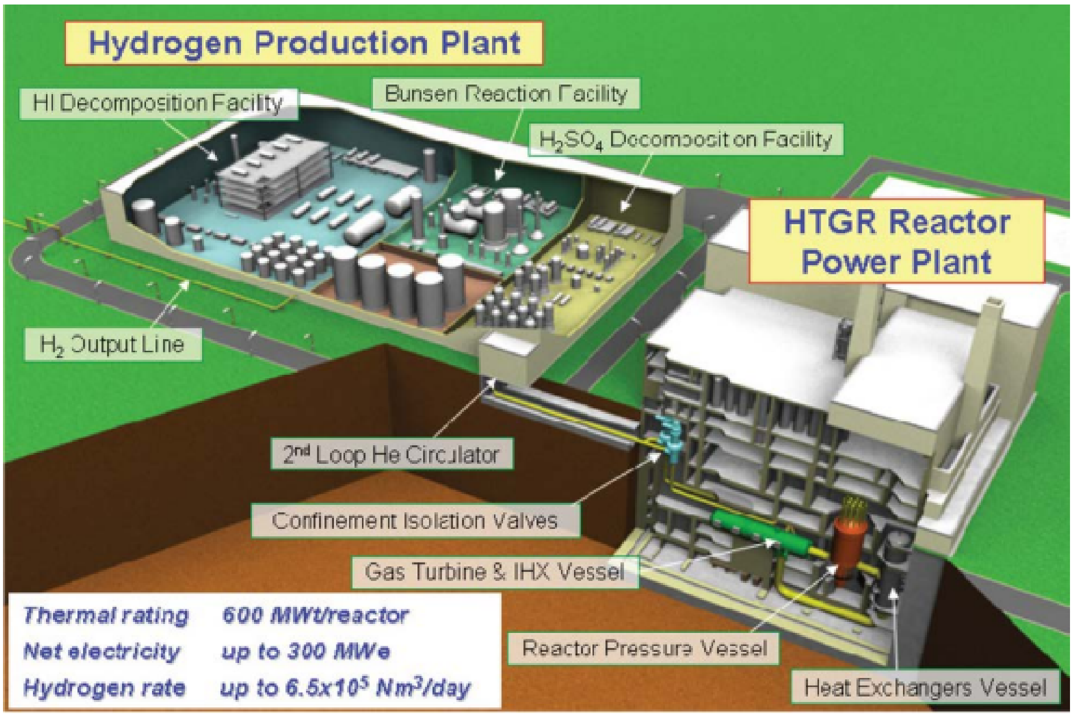


Figure 4.7: Conceptual 3D layout of an HTGR coupled with a Sulfur-Iodine hydrogen production plant [19].

4.7 The Baseline Case: Steam Methane Reforming (SMR) with CCS

To obtain a comprehensive study, nuclear technologies were compared to a Baseline case of hydrogen produced from fossil sources, which currently dominate the market. The chosen baseline is Steam Methane Reforming (SMR). To ensure a fair comparison regarding the ecological transition, fossil technology must be integrated with Carbon Capture and Storage (CCS) systems, generating Blue Hydrogen.

Operating Principle and Chemical Reactions

The SMR process extracts hydrogen from the molecules of hydrocarbon, typically natural gas (CH_4), by making them react with steam at extremely high pressure and temperature. The process involves two reactions:

- **Reforming Reaction (Endothermic):** Methane reacts with steam in the presence of a nickel-based catalyst at high temperatures between 700°C and 1000°C, producing a mixture of carbon monoxide and hydrogen (Syngas).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{4.15}$$

- **Water-Gas Shift Reaction (Exothermic):** To maximize hydrogen yield, the carbon monoxide is reacted with additional steam, in this case at lower temperatures (200-400°C), producing carbon dioxide and further hydrogen.

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{4.16}$$

CCS Integration and Parameters

Without CCS (the carbon dioxide abatement system), the output is referred to as Grey Hydrogen. This system emits approximately 9.5 kg of CO_2 for every kg of hydrogen produced. In the Baseline case, however, the exhaust gases are treated with solvents to capture up to 90% of the CO_2, which is then compressed and injected into geological formations. With carbon capture, the process produces Blue Hydrogen. This integration heavily impacts operating costs and reduces the overall efficiency of the plant, still leaving a residual emission quota of approximately 1-2 kg CO_2/kg H_2. Furthermore, this solution remains highly vulnerable to natural gas price fluctuations and future carbon taxation mechanisms, unlike the total energy independence offered by nuclear cogeneration[23].

Methodology and Techno-Economic Analysis

The primary objective of this chapter is to define the methodology used to evaluate the economic feasibility and technical performance of hydrogen production via nuclear energy. In this section, the analysis shifts to a quantitative and comparative level to understand the real potential of nuclear hydrogen.

The study is conducted using the *Hydrogen Economic Evaluation Programme* (HEEP) software, developed by the IAEA, which allows for the standardization of the Levelized Cost of Hydrogen (LCOH) calculation. By defining five specific case studies — comparing different types of nuclear reactors with traditional production methods based on fossil fuels — the technical and economic parameters that most influence the competitiveness of hydrogen will be analyzed.

The following sections will describe the details of the software used, the assumptions underlying the analyzed cases, and the fundamental technical and economic drivers for understanding the results that will be presented in the final chapter.

5.1 Introduction to IAEA HEEP Software

To economically evaluate the production of nuclear hydrogen, the *Hydrogen Economic Evaluation Programme* (HEEP) is a software developed by the International Atomic Energy Agency (IAEA), was utilized [24]. HEEP is a tool specifically designed to evaluate the technical performance and economic feasibility of large-scale hydrogen production using nuclear power plants.

The utilized software focuses on the specific aspects of nuclear production, allowing for the modeling of the direct interaction between the chosen reactor (the primary energy source) and the selected chemical plant. It is capable of analyzing the four main types of hydrogen production:

- Conventional low-temperature electrolysis;

- High-temperature steam electrolysis (HTSE);
- Thermochemical water splitting processes (e.g., S-I or Cu-Cl cycles);
- Conventional reforming (SMR).

Architecture and Calculation Models

The program is based on a modular approach and is structured into three main components through a dedicated graphical user interface (GUI) (Figure 5.1):

- **Pre-processing Module:** Allows the input of technical, chronological, and economic data separated into four infrastructure categories: the Nuclear Power Plant (NPP), the Hydrogen Generation Plant (HGP), potential storage (HS - Hydrogen Storage), and transport (HT).
- **Execution Module:** Performs mathematical calculations based on the Discounted Cash Flow (DCF) methodology.
- **Post-processing Module:** Outputs the final results by breaking down the weight of individual components on the total cost.

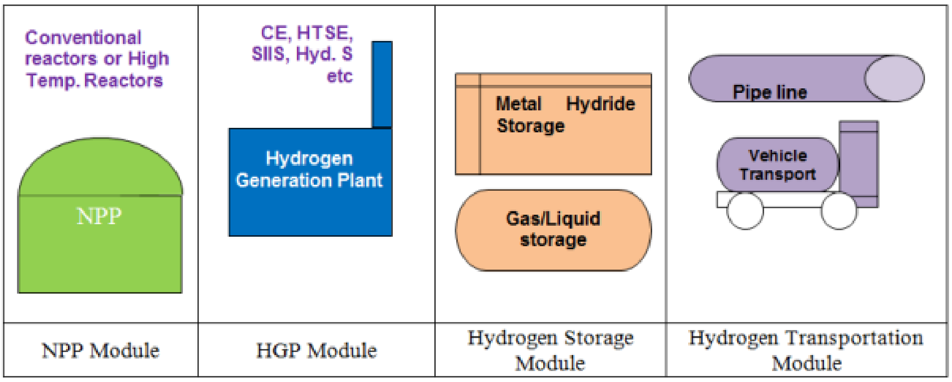


Figure 5.1: Main interface and modular structure of the IAEA HEEP software [24].

Calculation of the Levelized Cost of Hydrogen (LCOH)

The core of the program is the calculation of the discounted cost of hydrogen, commonly known as LCOH, or indicated in the software as LHGC (*Levelized Hydrogen Generation Cost*). HEEP also efficiently manages "dual-purpose" cogeneration plants: it initially calculates the levelized cost of the input nuclear energy, dividing it into $LUEC_e$ for electrical energy and $LUEC_t$ for thermal energy, and includes it as an operating and maintenance (O&M) cost in the hydrogen production module.

The Discounted Cash Flow model implemented in HEEP takes into account a wide range of macroeconomic and financial parameters:

- Discount rate and inflation rate;
- Equity to Debt ratio, with their respective interest rates;
- Income taxation and linear depreciation period (*Depreciation*);
- Capital costs (CAPEX) and operating and maintenance costs (OPEX), which include nuclear fuel reloads (front-end and back-end), refurbishment costs, and final plant decommissioning costs.

Thanks to this versatility, HEEP allows both the estimation of the unit cost of hydrogen and the conduction of in-depth sensitivity analyses. Therefore, it guarantees a transparent and standardized basis for comparing different nuclear-hydrogen couplings with each other and with fossil-based processes.

5.2 Definition of Study Cases

The analysis conducted using the IAEA's HEEP software involved the evaluation of a broad spectrum of technological and economic scenarios. The selection of these scenarios was made with the objective of simulating different sizes and types of reactors, from small modular reactors (SMRs) and heavy water reactors (CANDU) to large high-temperature gas-cooled reactors (HTGRs), coupling them with the most thermodynamically compatible hydrogen production technologies.

They were studied to understand which among the selected reactors and hydrogen production plants are the most robust in terms of costs and performance. A total of four nuclear cases were selected: SMR-LWR, CANDU, HTGR, and HTGR.

The conducted study serves not only to compare the various nuclear technologies with each other but also to make a direct comparison with the technologies most widely used today in hydrogen production: fossil fuel-based technologies. The latter, recognized as the baseline case, is the coupling of Steam Methane Reforming with Carbon Capture and Storage (SMR+CCS).

The cases analyzed in the study are the following:

- **Case 1:** Small Modular Reactor (SMR, NuScale VOYGR model) coupled with a low-temperature electrolysis plant (PEM, with evaluation of the Alkaline variant - AWE).
- **Case 2:** Pressurized Heavy Water Reactor (CANDU-600) coupled with a plant based on the Copper-Chlorine (Cu-Cl) hybrid thermochemical cycle.
- **Case 3:** High-Temperature Gas-cooled Reactor (HTGR, General Atomic Fulton model) coupled with a High-Temperature Steam Electrolysis (HTSE) plant.

- **Case 4:** High-Temperature Gas-cooled Reactor (HTGR, General Atomic Fulton model) coupled with a plant based on the Sulfur-Iodine (S-I) thermochemical cycle.
- **Baseline Case:** Production via Steam Methane Reforming (SMR) from natural gas, integrated with Carbon Capture and Storage (CCS) systems for "blue" hydrogen production.

Case	**Nuclear Reactor**	**Size (MW_{th})**	**Hydrogen Technology**	**Target Prod. (kg/y)**
Case 1	SMR (NuScale VOYGR)	250	PEM / Alkaline Electrolysis	11,700,000
Case 2	PHWR (CANDU-600)	2180	Cu-Cl Hybrid Cycle	40,000,000
Case 3	HTGR (General Atomic)	3000	HTSE Electrolysis	100,000,000
Case 4	HTGR (General Atomic)	3000	S-I Thermochemical Cycle	100,000,000
Baseline [25]	Natural Gas (Feedstock)	~516	SMR with CCS	100,000,000

Table 5.1: Summary of the defined study cases and selected technologies.

Each nuclear case was sized considering the optimal thermal and electrical interaction between the nuclear power plant (NPP) and the hydrogen generation plant (HGP), ensuring a balanced comparison. In the subsequent sections, the technical and economic parameters entered into the calculation model for each scenario will be detailed. Moreover, to evaluate the competitiveness of the nuclear technologies, was used a conventional baseline scenario based on Steam Methane Reforming (SMR) coupled with Carbon Capture and Storage (CCS), as an industrial benchmark. In the next sections, will be explained the technical and economic parameters entered into the calculation model for each case.

5.3 Main Technical Drivers

The reliability of the HEEP software is directly correlated to the accuracy of the technical parameters entered into the model. The technical drivers define the overall efficiency of the plant and serve to quantitatively describe the energy coupling between the nuclear power plant (NPP) and the hydrogen generation plant (HGP).

In the software interface (Figure 5.2), the structures to be displayed—such as the plants, transport, and storage—must first be selected, followed by the input of data regarding the electrical and thermal energy of the reactor that is diverted from the electrical grid and supplied to the hydrogen production plant.

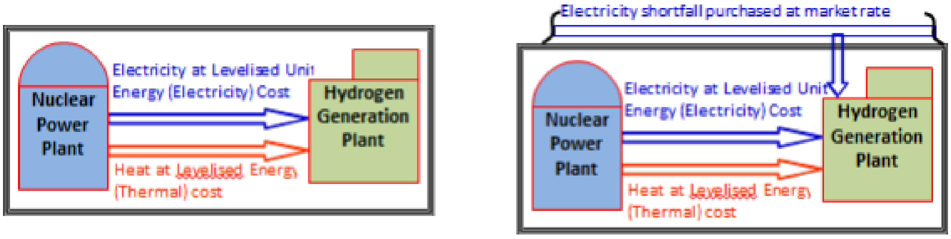
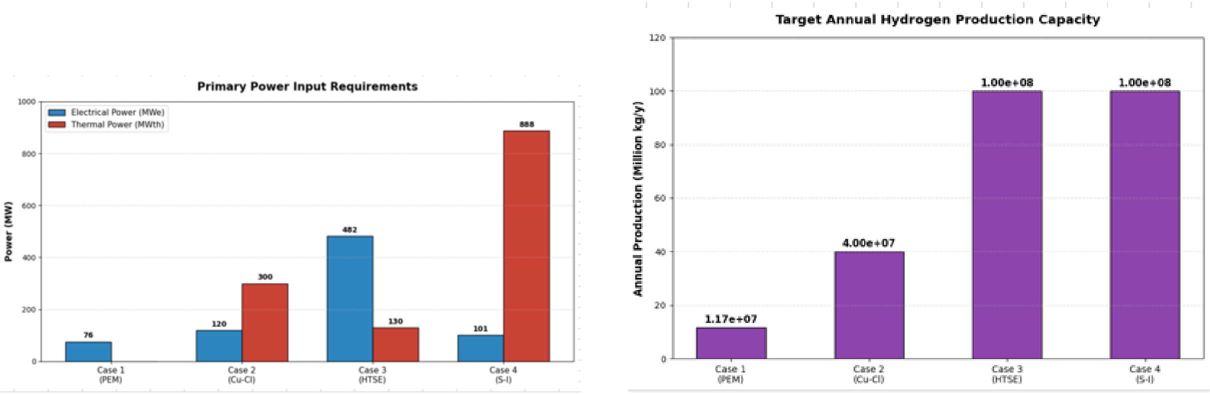


Figure 5.2: Input interface for the technical drivers and energy coupling parameters in HEEP [24].

Naturally, depending on the implemented technology, the energy requirements vary significantly:

- **Case 1 (SMR + PEM/AWE):** Low-temperature electrolysis is a purely electrical process; therefore, the plant does not require thermal energy (0 MW_{th}). To meet the production target of 11.5 million kg/year, the NuScale VOYGR reactor must dedicate almost its entire net electrical power (approximately 76 MW_e) to the electrolysis process.
- **Case 2 (CANDU + Cu-Cl):** The Copper-Chlorine hybrid cycle requires both a certain amount of electrical energy and a specific amount of thermal energy. Approximately 300 MW_{th} of medium-temperature heat is extracted from the heavy water reactor, in addition to the share of electrical energy necessary for the electrochemical reactions of the cycle.
- **Case 3 (HTGR + HTSE):** High-temperature steam electrolysis, instead, utilizes waste heat, thus reducing the required electrical work. For the target of 100 million kg/year, the plant requires about 130 MW_{th} of direct heat and a substantial electrical absorption of 480 MW_e from the General Atomic reactor.
- **Case 4 (HTGR + S-I):** The Sulfur-Iodine thermochemical cycle represents the most intensive coupling from a thermal perspective. For the same amount of hydrogen produced compared to Case 3 (100 million kg/year), the requirement shifts significantly towards heat: the process absorbs as much as 888 MW_{th} at very high temperatures and only 101 MW_e for auxiliary services.
- **Baseline Case (SMR + CCS):** Since no nuclear reactor is present, the technical parameters for this case focus on the conversion efficiency of natural gas (feedstock) and the energy consumption of the CO_2 capture unit, which is set at a standard abatement efficiency of 90%.

All the efficiency parameters, thermodynamic conversion rates, and nominal power capacities entered into the software were derived by cross-referencing scientific literature data with technical reports from international research institutions, including the Idaho National Laboratory (INL) [26], the United States Department of Energy (U.S. DOE) [27, 28], and the International Renewable Energy Agency (IRENA) [29].



(a) Power required (MW).

(b) Annual H_2 production.

Figure 5.3: Technical sizing drivers showing the power input requirements and the resulting target annual production capacities for the analyzed configurations.

5.4 Main Economic Drivers

Once the technical parameters and the various energy couplings have been defined, the subsequent phase of the analysis in HEEP requires addressing the economic aspects of all system components. The economic drivers are all those parameters that affect the final LCOH, as they determine the amortization of investment and operating costs over time.

The software interface dedicated to the economic aspect (Figure 5.4) allows defining a detailed financial structure for the entire project. The required parameters are divided into four macro-categories for the five chosen study cases:

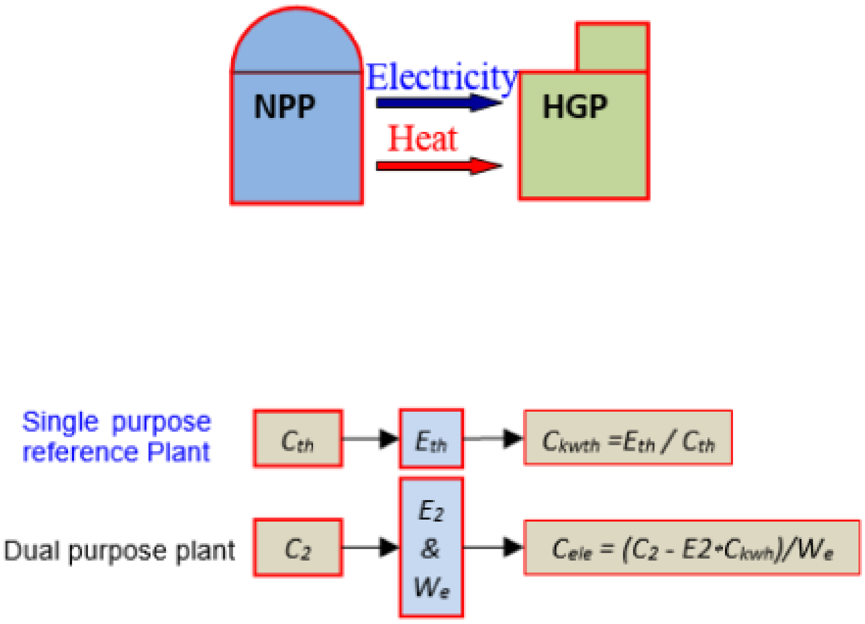


Figure 5.4: Input interface for the macroeconomic and financial parameters in HEEP [24].

- **Capital Expenditure (CAPEX):** Represents the *Overnight Capital Costs* for the construction of the nuclear power plant (NPP) and the hydrogen generation plant (HGP). For nuclear projects, a CAPEX in the order of billions of dollars is expected, making them highly capital-intensive investments compared to the reforming plant of the Baseline case. However, this initial disadvantage is offset by low long-term operating costs.
- **Operational, Maintenance, and Fuel Costs (OPEX):** This section includes the fixed and variable expenses required to operate the plant. This is where the main difference between the nuclear cases and the fossil case emerges. For nuclear technologies, the cost of the raw material, namely uranium, has a very low incidence on the final cost of hydrogen, estimated at around 0.15 $/kg. Conversely, in the Baseline case (SMR+CCS), the cost of natural gas used as feedstock represents the dominant expense and is also more subject to geopolitical market fluctuations.
- **Discount Rate and Financial Structure:** The cost of money is a critical parameter for nuclear projects. In the base model, a standard discount rate of 5% was set, also defining the ratio between equity and debt (*Equity to Debt ratio*) with their respective interest rates. Varying the discount rate, for example by raising it to 8%, entails a significant increase in the interest share, directly affecting the unit cost of hydrogen, while still keeping it competitive.

- **Plant Life and Decommissioning:** The useful life of the project radically changes the results. Modern nuclear reactors are designed to operate for 40 to 60 years (40 years + 20 in refurbishment). Simulations in HEEP demonstrate that extending the plant's amortization to 60 years allows for a considerable reduction in the incidence of CAPEX, leading to an LCOH reduction that can approach 0.50 \$/kg. The economic model also included the end-of-life dismantling costs (*Decommissioning*), which are spread over the kilograms of hydrogen produced.

All input economic values, especially the CAPEX of the individual reactors and the electrolyzers, were normalized to ensure an equilibrate comparison usign official estimates from the United States Department of Energy (DOE) [3] and IAEA PRIS documentation [30].

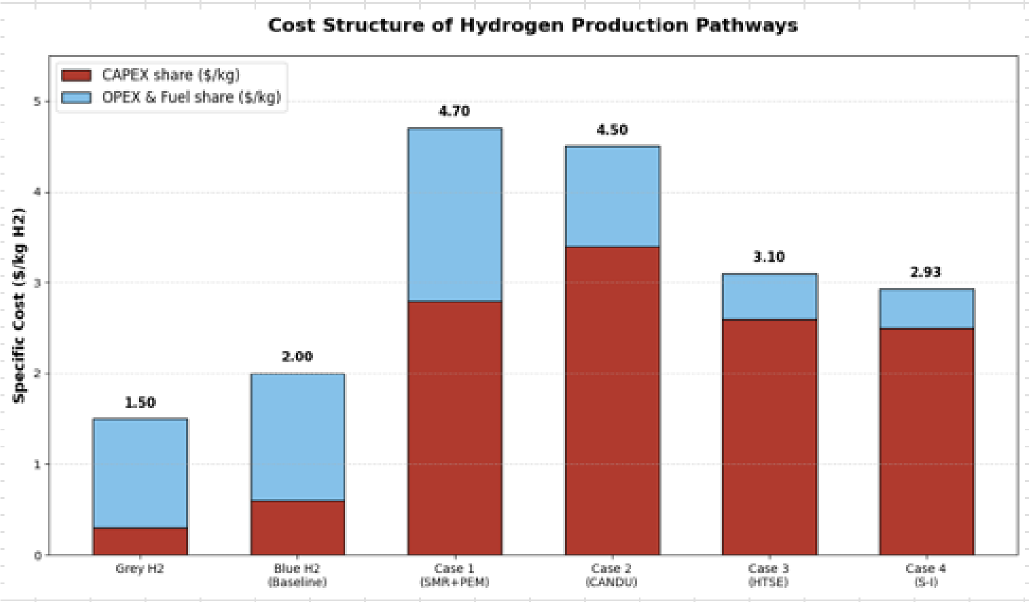


Figure 5.5: Cost Structure analysis illustrating the components of the specific hydrogen cost, distinguishing between capital investment (CAPEX share) and operating/fuel expenses (OPEX share).

5.5 Definition of Levelized Cost of Hydrogen (LCOH)

One of the most important parameters in this comparative economic study of different technologies is the Levelized Cost of Hydrogen (LCOH), indicated within the HEEP software by the acronym LHGC (*Levelized Hydrogen Generation Cost*).

The LCOH is the minimum price, at which hydrogen should be sold, to reach the break-even point at the end of the plant's useful life, covering all investment, operational, and financial costs, while simultaneously remunerating the invested capital.

The software applies the Discounted Cash Flow (DCF) methodology, calculating the ratio between the net present value of all the costs to which the system is subject over its entire lifetime and the total amount of hydrogen produced, which is also discounted. The general formula is:

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}} \tag{5.1}$$

Where the variables represent:

- I_t: Investment expenditures (CAPEX) incurred in year t;
- M_t: Operational and maintenance costs (OPEX) in year t;
- F_t: Fuel costs (uranium or natural gas) in year t;
- H_t: Quantity of hydrogen produced in year t (in kg);
- r: Discount rate, reflecting the cost of capital;
- n: Expected useful life of the plant (in years).

The HEEP software manages the F_t parameter, the fuel costs, for cogeneration nuclear plants by previously calculating the levelized cost of nuclear energy (*Levelized Unit Energy Cost* - LUEC), separating it into electrical and thermal energy, and allocating it as an operational cost to the hydrogen production plant.

This mathematical approach ensures that the LCOH calculation accounts for the time value of money, allowing for a direct, fair, and standardized comparison between capital-intensive investments (such as nuclear) and technologies primarily based on operational costs (such as natural gas reforming).

Results and Discussion

In this final chapter, the results obtained from the five study cases through simulations performed using the HEEP software are presented and subsequently discussed. The objective is to obtain a comparison among the various nuclear hydrogen production technologies and, subsequently, to compare them with the fossil fuels baseline case.

The analysis is divided into five phases: initially, evaluations of the thermodynamic performances are carried out, followed by the economic analysis of the LCOH. Subsequently, the sensitivity analysis on macroeconomic parameters is addressed, then an environmental impact assessment in terms of CO_2 emissions and, finally, an examination of the technological risks associated with the various processes.

6.1 Performance Analysis: Efficiency and Production

The initial phase of comparing the study cases focuses on technical performance, as well as mass and energy balances. The conversion efficiency from primary nuclear energy to the hydrogen vector varies significantly depending on the employed chemical technology, specific energy consumptions, and cogeneration dynamics.

In cogeneration configurations, extracting heat (Q_{th}) from the reactor's primary or secondary loop inevitably reduces the electrical power generated by the turbine. This electrical penalty (ΔP_e) is a function of the nominal thermodynamic efficiency (η_{th}) of the reactor's power cycle:

$$\Delta P_e = Q_{th} \times \eta_{th} \tag{6.1}$$

An analysis of the input data processed within the HEEP model reveals the specific thermodynamic sizing for each case:

- **Cases 1 and 1a: SMR (NuScale) with PEM and Alkaline Electrolysis.** The initial fuel load (m_{fuel}) for the NuScale reactor (37 assemblies, 250 kg each) is evaluated as:

$$m_{fuel} = 37 \text{ assemblies} \times 250 \text{ kg/assembly} = 9.250 \text{ kg} \tag{6.2}$$

The facility is exclusively powered by electricity. To ensure simulation stability and cover the reactor's auxiliary loads, a net electrical capacity (P_e) of 76 MW_e is dedicated to hydrogen production. Assuming a Capacity Factor (CF) of 95%, the equivalent annual operating hours (h_{eq}) equate to 8322 hours. For the PEM electrolyzer, factoring in the Balance of Plant (BoP) consumption, the specific energy requirement (C_{spec}) is 55.5 kWh_e/kg. For the Alkaline variant (AWE), the consumption is 55 kWh_e/kg. The annual hydrogen yield (M_{H_2}) for the AWE case is calculated as:

$$M_{H_2,\text{AWE}} = \frac{P_e \times h_{eq}}{C_{spec}} = \frac{76.000 \text{ kW} \times 8.322 \text{ h/year}}{55 \text{ kWh/kg}} \approx 11.498.618 \text{ kg/year} \tag{6.3}$$

- **Case 2: CANDU-600 with Cu-Cl Hybrid Cycle.** The heavy water reactor requires a substantial fuel mass, distributed across 380 channels with 12 bundles each (19.3 kg per bundle):

  $$m_{fuel} = 380 \times 12 \times 19{,}3 \text{ kg} \approx 88.000 \text{ kg} \tag{6.4}$$

  Diverting 300 MW_{th} of heat for the Cu-Cl process incurs an electrical penalty. Given the CANDU's efficiency of 29.3%, the lost electrical power is:

  $$\Delta P_e = 300 \text{ MW}_{th} \times 0{,}293 = 87{,}9 \text{ MW}_e \tag{6.5}$$

  This reduces the net available electrical power from 638 MW_e to 550.1 MW_e. The Cu-Cl plant requires 60 kWh_{th}/kg and 24 kWh_e/kg. Operating with a 90% CF (7884 hours/year), the maximum annual production limited by the thermal input is:

  $$M_{H_2} = \frac{300.000 \text{ kW}_{th} \times 7.884 \text{ h/year}}{60 \text{ kWh}_{th}\text{/kg}} = 39.420.000 \text{ kg/year} \tag{6.6}$$

  Consequently, the nominal electrical power required by the chemical plant is strictly sized at:

  $$P_{e,H_2} = \frac{39.420.000 \text{ kg/year} \times 24 \text{ kWh}_e\text{/kg}}{7.884 \text{ h/year}} = 120.000 \text{ kW} = 120 \text{ MW}_e \tag{6.7}$$

- **Case 3: HTGR with HTSE.** For high-temperature scenarios, plant sizing is reverse-engineered from the target of 10^8 kg/year. With 7884 operating hours, the required hourly mass flow rate ($\dot{m}_{H_2}$) is:

$$\dot{m}_{H_2} = \frac{100.000.000 \text{ kg/year}}{7.884 \text{ h/year}} = 12.684 \text{ kg/h} \tag{6.8}$$

The HTSE process demands 38 kWh_e/kg and 10 kWh_{th}/kg. The continuous power requirements are:

$$P_{e,H_2} = 12.684 \text{ kg/h} \times 38 \text{ kWh}_e\text{/kg} \approx 482 \text{ MW}_e \tag{6.9}$$

$$Q_{th,H_2} = 12.684 \text{ kg/h} \times 10 \text{ kWh}_{th}\text{/kg} \approx 130 \text{ MW}_{th} \tag{6.10}$$

Applying the HTGR's efficiency ($\eta = 38.7\%$), the thermal extraction reduces the nominal electrical power by only 50.3 MW_e (130 × 0.387), leaving 1109.7 MW_e available for the grid.

- **Case 4: HTGR with S-I Cycle.** This thermochemical cycle requires 70 kWh_{th}/kg and only 8 kWh_e/kg for auxiliary systems. Using the same hourly mass flow rate (12.684 kg/h), the power inputs are:

$$P_{e,H_2} = 12.684 \text{ kg/h} \times 8 \text{ kWh}_e\text{/kg} \approx 101 \text{ MW}_e \tag{6.11}$$

$$Q_{th,H_2} = 12.684 \text{ kg/h} \times 70 \text{ kWh}_{th}\text{/kg} \approx 888 \text{ MW}_{th} \tag{6.12}$$

The massive extraction of 888 MW_{th} results in a severe electrical penalty:

$$\Delta P_e = 888 \text{ MW}_{th} \times 0{,}387 = 343{,}6 \text{ MW}_e \tag{6.13}$$

Consequently, the new electrical rating of the plant drops from 1160 MW_e to 816.4 MW_e. However, bypassing the electrical power cycle for hydrogen production maximizes the overall thermodynamic efficiency.

As a preliminary comparison of the selected nuclear technologies, Figure 6.1 illustrates the baseline thermodynamic efficiency (η_{th}) of the primary power cycles for each reactor type, before any thermal extraction for hydrogen production.

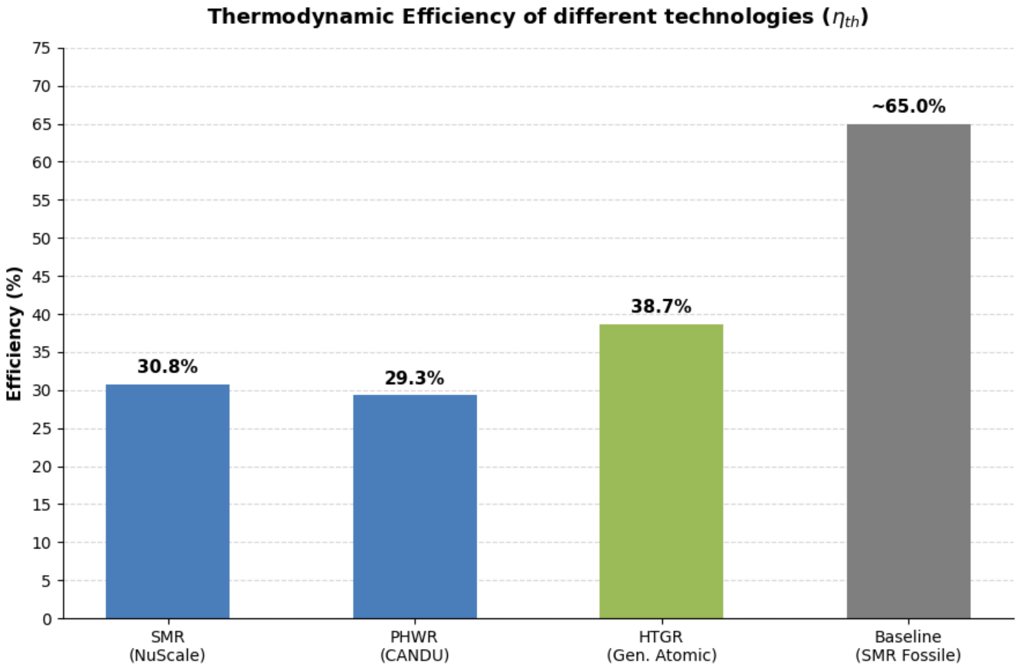


Figure 6.1: Thermodynamic efficiency of the selected primary energy sources.

Case Study	NPP Rating (MW_{th} / MW_e)	Efficiency (%)	HGP Heat Cons. (MW_{th})	HGP Elec. Req. (MW_e)	H_2 Generation (kg/y)
Case 1: SMR + PEM	250 / 77	30.8	0	76	1.17×10^7
Case 1a: SMR + AWE	250 / 77	30.8	0	76	1.15×10^7
Case 2: CANDU + Cu-Cl	2180 / 638	29.3	300	120	4.00×10^7
Case 3: HTGR + HTSE	3000 / 1160	38.7	130	480	1.00×10^8
Case 4: HTGR + S-I	3000 / 1160	38.7	888	101	1.00×10^8
Baseline: SMR + CCS [25]	- / -	~65.0	~516	~22	1.00×10^8

Table 6.1: Summary of technical parameters, nominal efficiencies, and energy requirements.

The data summarized in Table 6.1 highlights the huge difference in production scales and energy routing among the analyzed configurations. To better understand these variations and the impact of the chosen chemical process, it is crucial to break down the energy consumption. Figure 2.3 illustrates the specific energy demand per kilogram of hydrogen produced, clearly distinguishing between the electrical input (blue) and the thermal input (red).

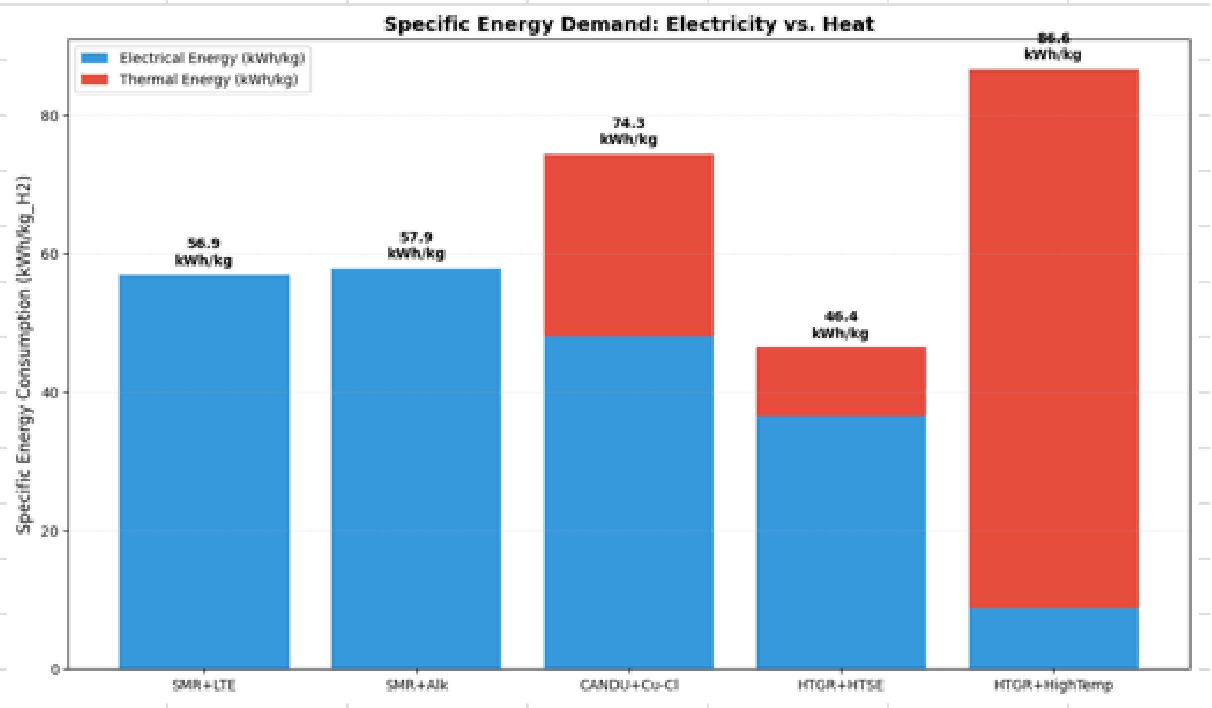
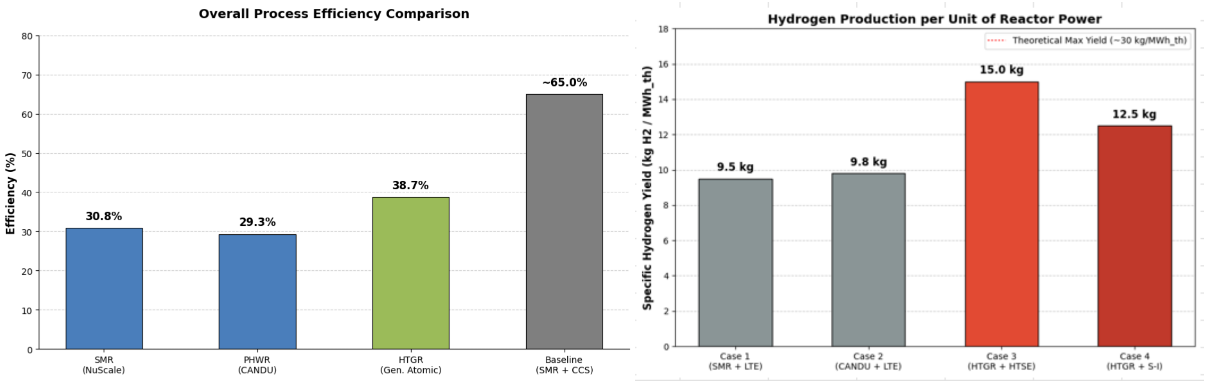


Figure 6.2: Specific energy demand comparison per kilogram of hydrogen produced, highlighting the electricity (blue) vs. heat (red) requirements for each case study.

As evident from the chart, while low-temperature electrolysis (Cases 1 and 1a) relies entirely on electrical power, high-temperature thermochemical processes shift the burden towards direct thermal energy. This shift profoundly affects the overall performance of the integrated plant. Therefore, the technical analysis concludes by comparing the two ultimate performance metrics: the overall process efficiency and the specific hydrogen yield per unit of nuclear power, as visualized in Figure 6.3.



(a) Overall process efficiency (% LHV).

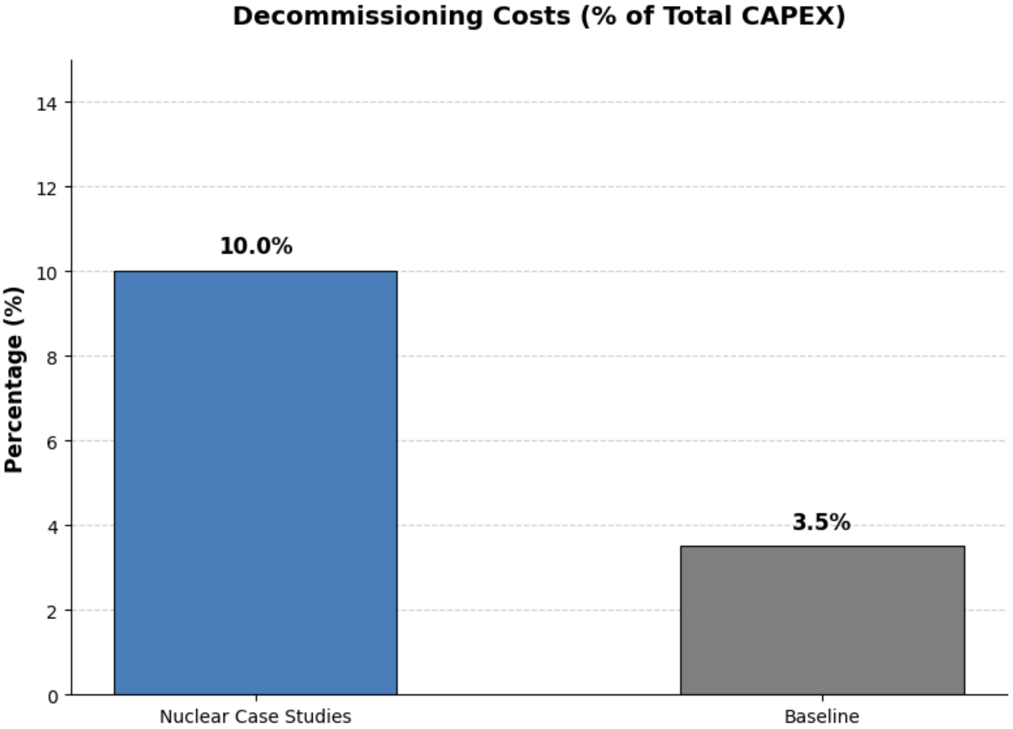
(b) Specific Hydrogen Yield per MWh_{th} of reactor power.

Figure 6.3: Key performance indices showing the thermodynamic efficiency and operational yield for selected study cases.

6.2 Economic Analysis: Cost Comparison and LCOH

Nuclear cogeneration has demonstrated high performance in terms of thermodynamic analysis, but the actual feasibility of these technologies is dictated by their economic sustainability. This assessment was conducted using the IAEA HEEP software, which calculates the Levelized Cost of Hydrogen (LCOH) by integrating capital expenditures (CAPEX), operation and maintenance (O&M) costs, fuel costs, and financial charges over the entire operational lifetime of the plant.

This economic model relies on standardized parameters: a discount rate of 5%, a construction period of 5 years, and a plant operational lifetime of 40 years were assumed. The debt-to-equity ratio is set at 70/30 with an interest rate of 7%. For all nuclear scenarios, the end-of-life decommissioning cost was estimated at 10% of the initial capital cost, as illustrated in Figure 6.4.



Source: Adapted from IAEA (Nuclear) and GCCSI/IEAGHG (CCS) technical reports.

Figure 6.4: End-of-Life Decommissioning Costs comparison across the evaluated case studies.

6.2.1 Initial Investment (CAPEX) Comparison

The main obstacle to the utilization and deployment of nuclear hydrogen is the massive initial investment required, known as the Overnight Capital Cost (OCC). In the nuclear sector, CAPEX is the dominant cost driver and often accounts for more than 50% of the final levelized cost.

Figure 6.5 highlights the difference in investments between fossil fuels and advanced nuclear technologies.

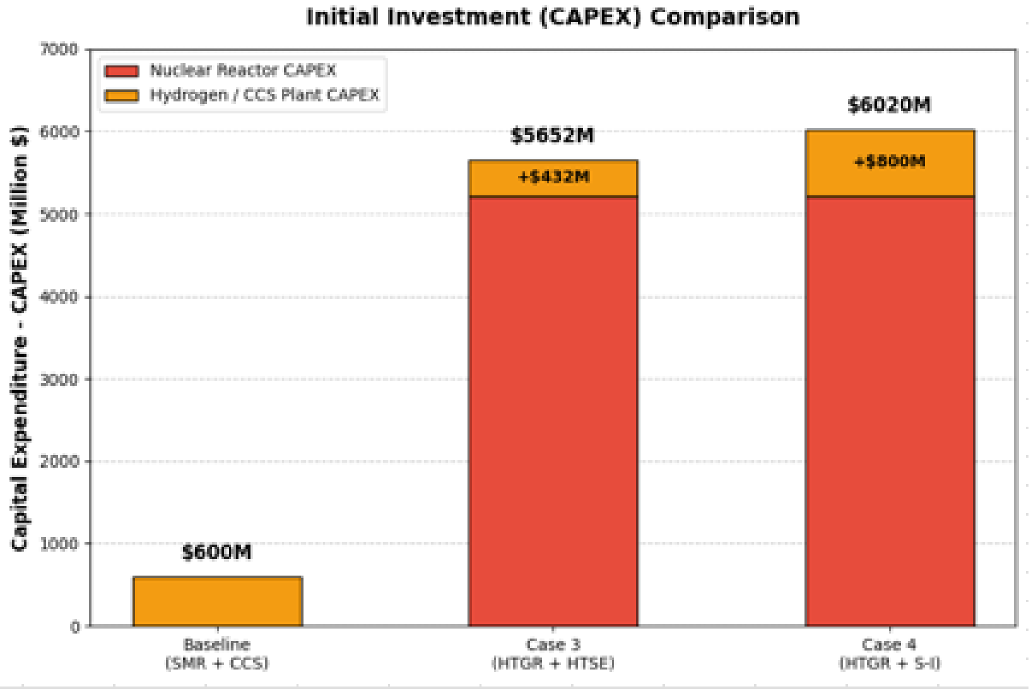


Figure 6.5: Initial Investment (CAPEX) comparison highlighting the capital-intensive nature of nuclear configurations.

The Baseline case (gas-fired SMR with CO2 capture), being the most widely used, represents a relatively low-cost entry option, requiring approximately $600 million. Conversely, high-temperature nuclear cases require nearly ten times the capital. The HTSE plant (Case 3) reaches $5,652 million, while the S-I thermochemical cycle (Case 4) exceeds $6,020 million. These figures reflect the extremely high cost of advanced materials needed to withstand extreme temperatures and corrosive environments.

6.2.2 Operational Costs and Market Vulnerability

However, basing the study solely on initial investments would be a disadvantage, as the dynamics reverse drastically when analyzing fuel costs and operational expenses (O&M) over the long term.

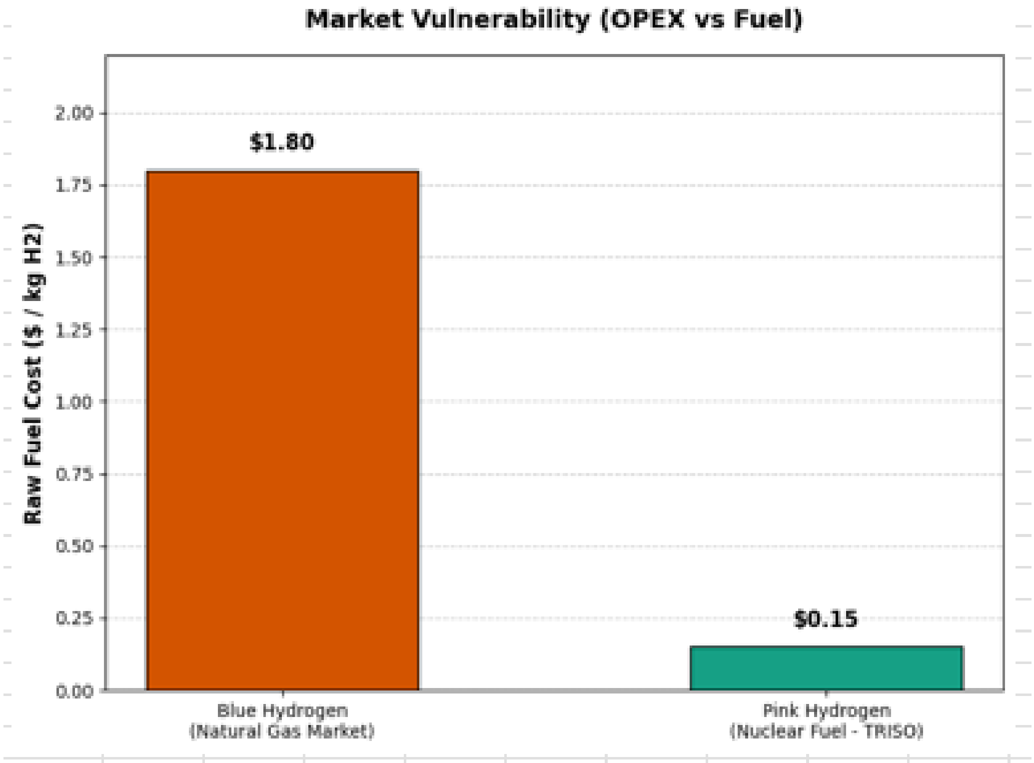
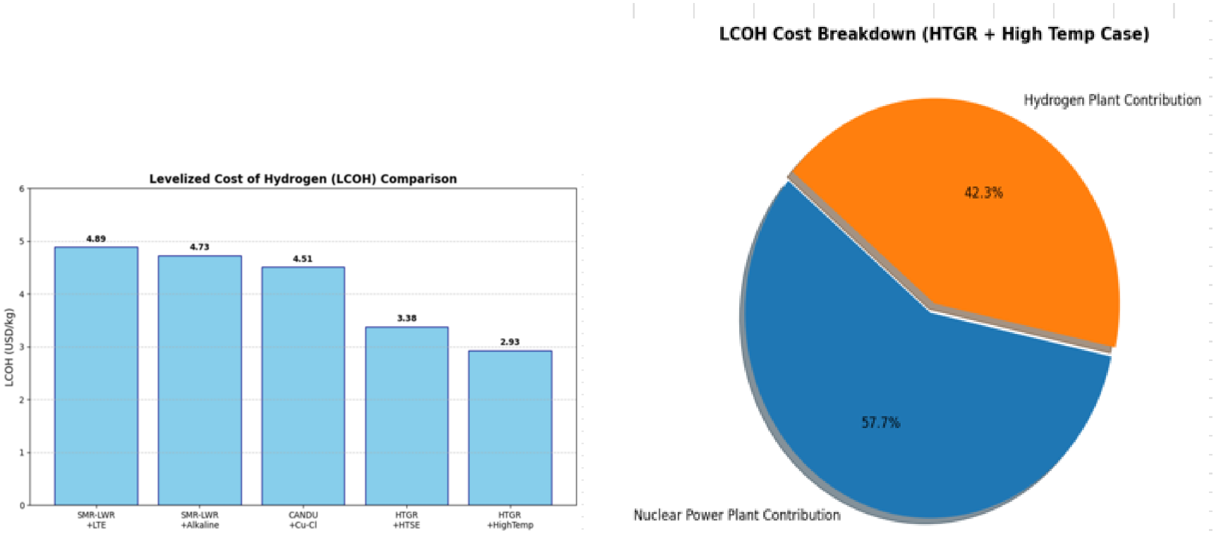


Figure 6.6: Market Vulnerability analysis showing the impact of fuel costs versus O&M expenses.

As shown by the market vulnerability analysis in Figure 6.6, the use of fossil fuels is heavily dependent on price fluctuations: the raw material (natural gas) accounts for as much as 1.80 $/kg of the hydrogen cost. Nuclear power, on the other hand, offers significant financial stability: the fuel cost has a negligible impact, weighing only 0.15 $/kg.

6.2.3 Levelized Cost of Hydrogen (LCOH)

The ultimate metric for comparing technologies is the Levelized Cost of Hydrogen (LCOH), as it balances the enormous CAPEX of nuclear power with its high operational efficiency. Since HTGR reactors have very high thermal efficiency, they require less energy to produce one kilogram of hydrogen.



(a) LCOH Comparison across all cases.

(b) LCOH Cost Breakdown.

Figure 6.7: Levelized Cost of Hydrogen (LCOH) evaluation and internal cost breakdown.

The HEEP results confirm that the high efficiency largely compensates for the initial capital. While low-temperature nuclear electrolysis systems (Cases 1 and 1a) struggle to drop below 4.70 \$/kg, high-temperature configurations dominate the comparison. Case 4 (very high-temperature HTGR) achieves an extremely competitive LCOH of 2.93 \$/kg, surpassing even the fossil baseline scenario. From a purely economic perspective, the use of direct heat via HTGR reactors proves to be the most promising and profitable solution in the long term.

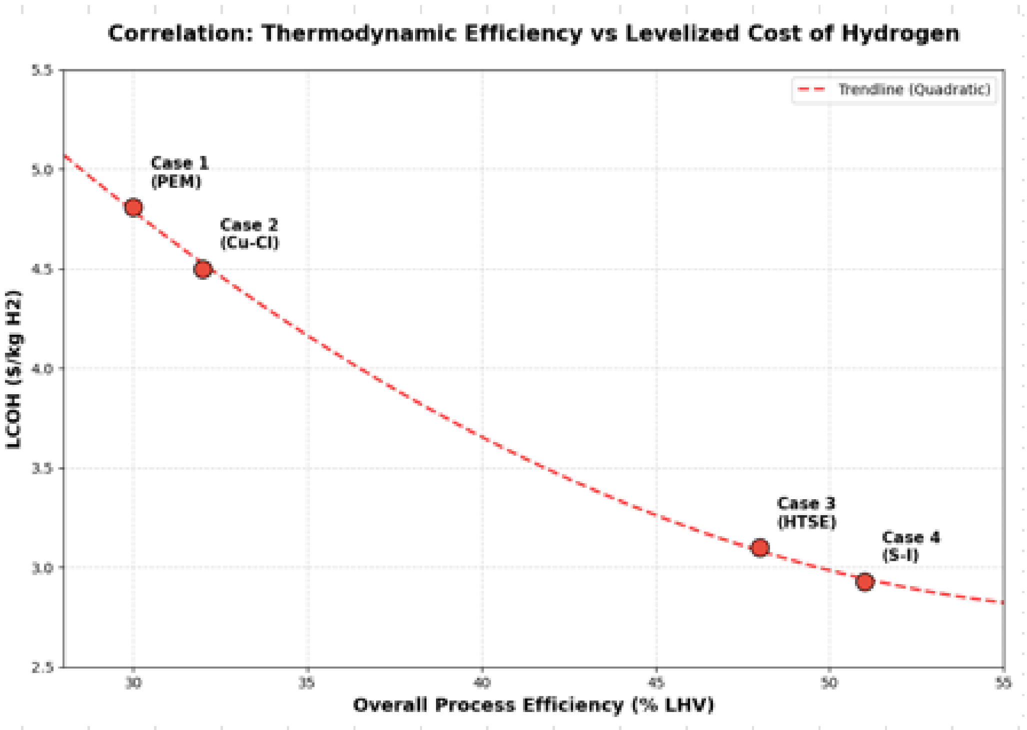


Figure 6.8: Correlation between the overall thermodynamic process efficiency and the resulting Levelized Cost of Hydrogen (LCOH), highlighting the economic advantage of high-temperature configurations.

6.3 Sensitivity Analysis

The economic analysis results presented in the previous section are based on deterministic and stable assumptions (5% discount rate, 40-year operating life, etc.). However, large-scale energy projects, particularly nuclear ones, can be subject to financial uncertainties and potential construction delays. To evaluate the robustness of the Levelized Cost of Hydrogen (LCOH), a sensitivity analysis was conducted on the most critical input parameters, modifying them one at a time to understand how and to what extent they can alter the final result.

The analysis was conducted using the highest-performing scenario as a reference, namely Case 4: HTGR (High-Temperature Gas-cooled Reactor), with a baseline LCOH of 2.93 $/kg, and tested the impact of three macroeconomic variations:

- **CAPEX:** a 20% increase from the standardized initial data was assumed to simulate potential engineering contingencies or construction delays (typical of "First-of-a-kind" reactors).
- **Discount Rate:** it was raised from 5% (HEEP standardized scenario) to 8%, simulating a more conservative financial scenario with a higher cost of debt.
- **Operating Life:** it was extended from 40 to 60 years, a highly realistic assumption

for modern nuclear reactors, which frequently obtain license extensions.

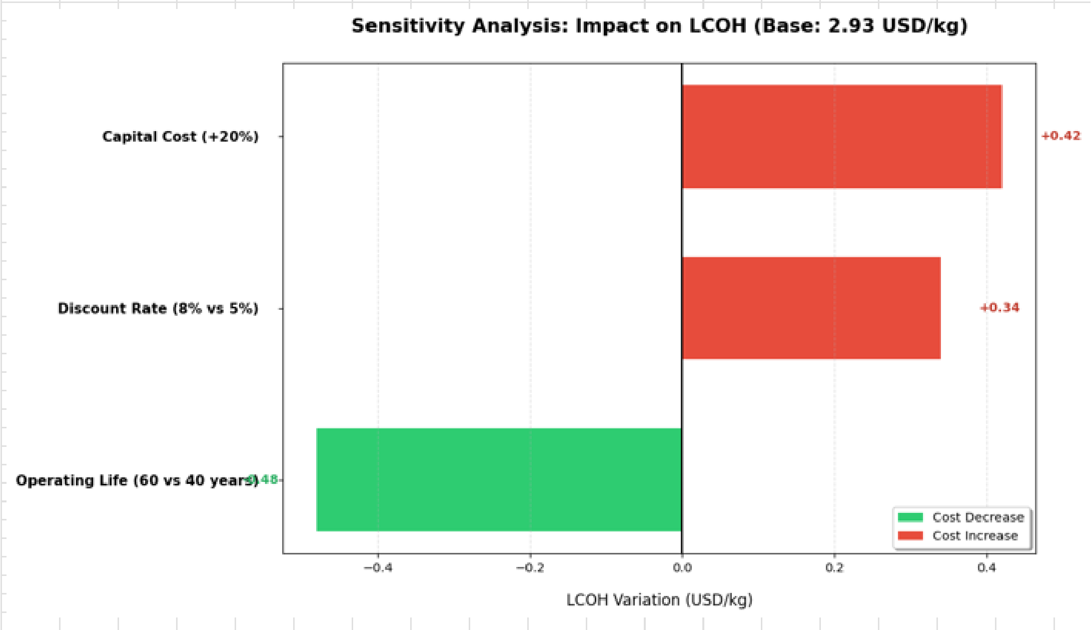


Figure 6.9: Sensitivity analysis (Tornado chart) illustrating the impact of key macroeconomic variables on the baseline LCOH of the HTGR configuration.

The chart illustrates the impact of each variable on the final cost. As expected for capital-intensive technologies, a 20% increase in CAPEX represents the major risk, increasing the LCOH by 0.42 $/kg. Furthermore, an unfavorable financial market (8% discount rate) penalizes the project, causing a cost increase of 0.34 $/kg. This demonstrates how government support and favorable financing rates are fundamental for the initial competitiveness of nuclear power.

Conversely, the chart highlights the enormous long-term potential of these infrastructures: extending the plant's operating life to 60 years has an extremely beneficial effect on costs, allowing the initial capital to be amortized over two additional decades of production and reducing the LCOH by almost half a dollar (-0.47 $/kg). In this optimized configuration, the cost of nuclear hydrogen would drop below 2.50 $/kg, making it one of the most economical and stable options globally.

6.4 Environmental Analysis: Avoided CO2 and Decommissioning

In the previous section, the economic analysis demonstrated the long-term competitiveness of nuclear cogeneration. However, another driving factor for the implementation of these technologies is their environmental impact. The primary goal of the emerging hydrogen infrastructure is the deep decarbonization of hard-to-abate industrial sectors.

6.4.1 Emissions Comparison and Avoided CO_2

To evaluate the environmental benefit, the direct operational emissions of nuclear technologies (Pink/Purple Hydrogen) were compared with the current standards of the fossil fuel industry (Grey and Blue Hydrogen).

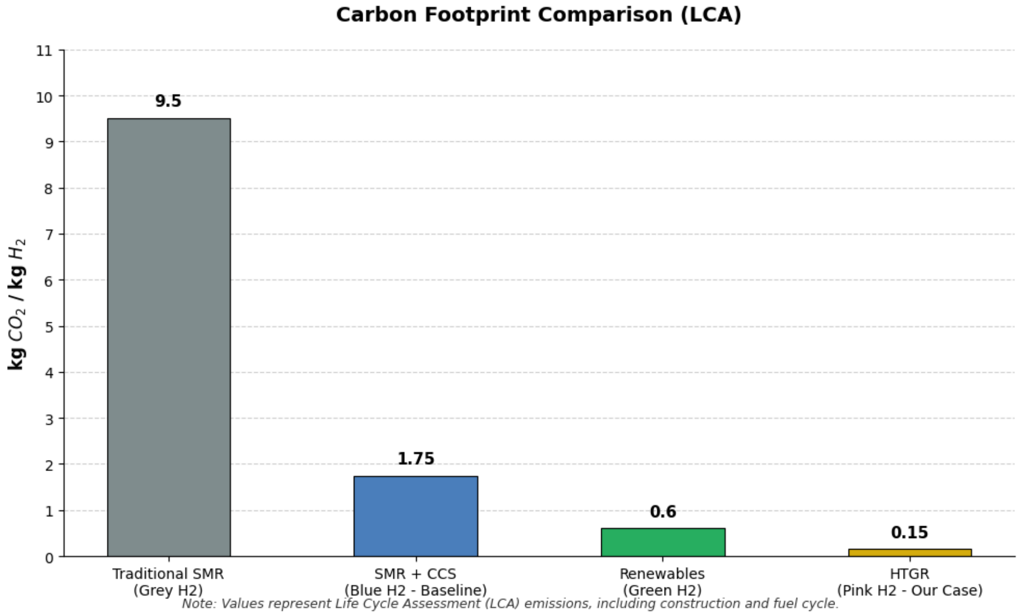


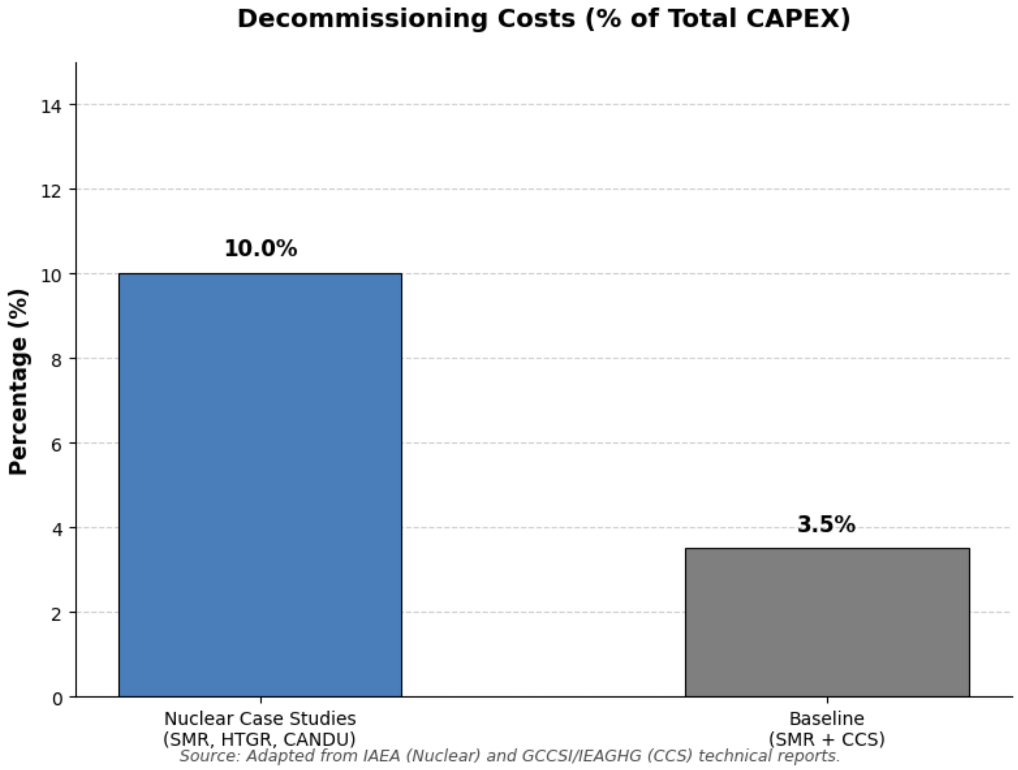
Figure 6.10: CO_2 Emissions Comparison (kg CO_2 / kg H_2) across different production pathways.

The comparison of emission profiles highlights the significant gap between fossil-based and low-carbon technologies. While the Grey H_2 scenario is characterized by high carbon intensity (9.5 kg CO_2/kg H_2), the Blue H_2 baseline reduces this impact to 1.75 kg CO_2/kg H_2 via CCS, though it remains limited by the thermodynamic constraints of capture systems.

For the HTGR system analyzed was adopted LCA-based approach, accounting for a marginal footprint of 0.15 kg CO_2/kg H_2 instead of assuming zero emissions. Even with this conservative assumption, the industrial-scale environmental benefits are huge. A target production of 100,000 tons, of hydrogen per year, is given; the HTGR plant avoids around 935,000 tons of CO_2 compared to the traditional SMR baseline scenario. The savings remain important even against the Blue H_2 baseline, with over 160,000 tons of avoided emissions annually driving the production process toward nearly total decarbonization.

6.4.2 Decommissioning Impact and Waste Management

A comprehensive environmental analysis must also consider the entire life cycle of the plant, including the end-of-life phase. As anticipated in the economic analysis, the decommissioning costs for nuclear reactors were conservatively estimated at 10% of the initial CAPEX.



Source: Adapted from IAEA (Nuclear) and GCCSI/IEAGHG (CCS) technical reports.

Figure 6.11: End-of-Life Decommissioning Costs comparison highlighting the conservative 10% assumption for nuclear facilities.

Unlike fossil fuel plants, which often leave long-term environmental liabilities, nuclear regulations mandate the safe dismantling and total restoration of the site (greenfield status). Furthermore, it is important to contextualize the end-of-life impact relative to other clean sources. While renewable energy systems currently face significant recycling challenges regarding bulky waste (e.g., fiberglass wind turbine blades and degraded solar panels), the extremely high energy density of nuclear power translates into a minimal volume of physical waste per unit of energy produced.

Modern SMRs and HTGRs are designed from the outset with modular configurations that simplify and accelerate the dismantling process, safely isolating irradiated materials and minimizing the final waste volume. This comprehensive regulatory and engineering framework makes Pink Hydrogen a sustainable option not only during its operational phase but throughout its entire life cycle.

6.5 Technological Limits and Risks

Although thermodynamic and economic studies have highlighted the importance and potential of nuclear cogeneration for pink/purple hydrogen production, implementing these technologies on a commercial scale faces major engineering and regulatory limitations. To ensure a comprehensive evaluation, it is necessary to analyze the technological limits and risks associated with the selected nuclear reactors, with particular attention to HTGRs.

6.5.1 Technology Readiness Level

The first obstacle these technologies encounter is related to their technological maturity. Light water reactors, in this case SMR-LWRs, and heavy water reactors, such as CANDUs, exhibit high technological maturity and a very low development risk, as they are based on decades of operational experience. However, as extensively demonstrated in previous chapters, they present lower efficiency for hydrogen production compared to the other evaluated cases.

Conversely, HTGRs offer a better compromise between high efficiency and production costs, but they carry a higher technological risk compared to LWRs due to their low technological maturity in the commercial sector. Further evolutions of HTGRs, such as VHTRs (Very High Temperature Reactors), hold a much higher theoretical potential but are currently at a pure research and development R&D stage, entailing a very high engineering risk.

6.5.2 Material Challenges and Corrosion

The highest-performing configurations, namely HTGRs, require heat extraction at extremely high temperatures, ranging between 800°C and 1000°C. This imposes extreme thermal and mechanical stresses on the materials of the primary components.

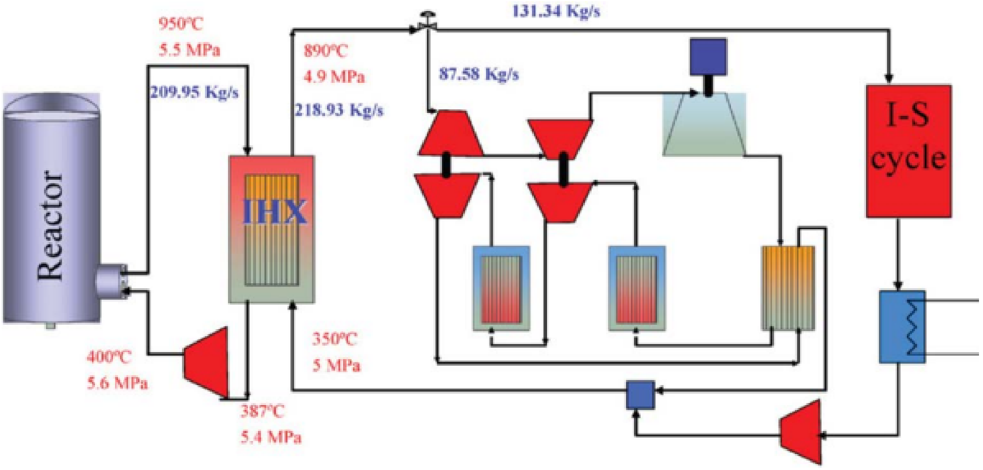


Figure 6.12: Schematic representation of a VHTR nuclear reactor coupled to the Sulfur-Iodine thermochemical cycle.[31]

Furthermore, coupling the reactor with thermochemical cycles, such as the Sulfur-Iodine (S-I) cycle, introduces a significant chemical risk: the process requires handling highly corrosive acids (sulfuric acid and hydroiodic acid) at high temperatures, creating an additional challenge for these technologies. Currently, the lack of commercial materials (such as advanced ceramics or superalloys) capable of withstanding this dual thermal and corrosive stress over the long term represents a substantial bottleneck.

6.5.3 Safety and Plant Coupling

Another critical risk stems from the coupling—or interface—between the nuclear island and the chemical plant. The proximity of a reactor to a facility that processes, stores, and moves large quantities of explosive gases (hydrogen and oxygen) demands strict safety paradigms.

It is therefore essential to design foolproof Intermediate Heat Exchangers (IHX) to ensure two fundamental functions: preventing radioactive tritium contamination from migrating into the produced hydrogen, and, conversely, preventing the accidental ingress of corrosive chemicals or flammable gases into the reactor core.

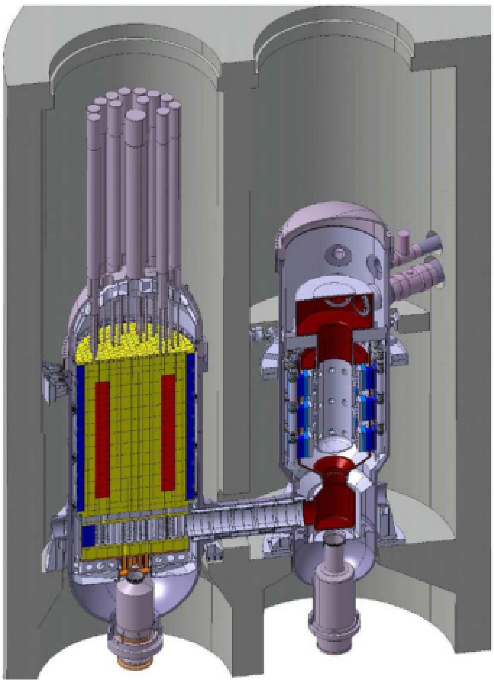


Figure 6.13: Example of a VHTR primary circuit showing the reactor pressure vessel and the Intermediate Heat Exchanger (IHX) unit.[31]

6.5.4 Economic and Supply Chain Risks

Finally, the technical challenges listed above translate directly into financial risks. Being "First-of-a-kind" (FOAK) plants, the uncertainty regarding construction times and regulatory approvals (licensing) is extremely high.

Added to this is the necessity to develop an entirely new supply chain, for example, for the large-scale production of the TRISO fuel required to operate advanced gas-cooled reactors.

Conclusions

The need to decarbonize hard-to-abate industrial sectors has made hydrogen an energy vector of primary importance for the energy transition. However, for it to become a viable green and/or sustainable solution, its production must be decoupled from the use of fossil fuels. In this context, the present study explored the advantages of nuclear cogeneration for hydrogen production, evaluating various nuclear technologies through comparative thermodynamic, economic, and environmental analyses.

The obtained results demonstrate that the competitiveness of nuclear hydrogen production is driven by three key factors: the reactor outlet temperature, the overall system efficiency, and the cost structure. Initially, light water (SMR-LWR) and heavy water (CANDU) reactors were analyzed. Despite possessing high technological maturity and low engineering risk, they are limited by their low operating temperatures. They can, however, be utilized to power conventional electrolysis, resulting in lower thermodynamic efficiencies and a less competitive Levelized Cost of Hydrogen (LCOH) in the long term.

Conversely, the study identified high-temperature reactors (HTGRs and, prospectively, VHTRs) as the most successful solution in this field. Their ability to provide direct heat at temperatures up to 1000°C allows them to power advanced processes, such as High-Temperature Steam Electrolysis (HTSE) and thermochemical cycles (like the Sulfur-Iodine cycle). Although these configurations require a very high initial investment (CAPEX), estimated at over $5.6 billion for an integrated plant, their high thermodynamic efficiency compensates for the initial cost. The HEEP software results indicate that the HTGR can achieve an LCOH of 2.93 $/kg, making it economically superior not only to other nuclear technologies but even to the baseline fossil scenario (natural gas SMR with CO_2 capture), which is heavily vulnerable to fuel price fluctuations.

From an environmental perspective, the benefit is evident: replacing fossil plants with HTGR cogeneration would avoid up to 935,000 tons of direct CO_2 emissions per year for a single plant producing 100,000 tons of hydrogen.

However, as highlighted in the risk analysis, the commercial-scale implementation of

HTGRs and thermochemical processes has yet to overcome significant technological obstacles. Handling highly corrosive materials at high temperatures requires advanced materials that are not yet commercialized. Furthermore, the design of foolproof Intermediate Heat Exchangers (IHX) will be crucial to ensure safety and prevent radioactive contamination of the produced hydrogen.

In conclusion, high-temperature nuclear cogeneration currently represents the best technical, economic, and environmental compromise for the massive production of clean hydrogen. Overcoming current engineering challenges and optimizing the supply chain (such as for TRISO fuel) will be crucial to transforming this promising technology into the pillar of a zero-emission global economy.

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