FACULTY OF TECHNOLOGY

SMR-TECHNOLOGIES IN HYDROGEN PRODUCTION

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ABSTRACT

SMR-technologies in hydrogen production

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This thesis goes out to explore the possibility of using small modular nuclear reactors (SMRs) in hydrogen production for industrial needs. Different types of hydrogen production technologies are examined in the thesis alongside small modular nuclear reactors. This work has been done to constitute an understanding of the requirements and limitations of nuclear hydrogen production in industrial settings. Additionally, the environmental impacts of nuclear hydrogen production methods are compared to traditional hydrogen production methods. The thesis has been done as a literature review.

As society faces the problems of rising greenhouse gas emissions in the form of global warming, the importance of environmentally friendly energy solutions has increased. In recent years, the interest for the hydrogen economy has grown. Hydrogen has been introduced as an interesting resource for multiple energy applications. For example, hydrogen fuel cells are seen as a prospective option in the decarbonization of the transportation industry. Traditional hydrogen production methods rely on fossil fuels. The future development however is focused on water electrolysis since it produces almost pure hydrogen and is considered the most environmentally friendly hydrogen production technology. Water electrolysis is an energy intensive process. In this thesis, nuclear technologies are presented as a way of supplying the energy for hydrogen production instead of fossil fuels.

This thesis presents benefits of using SMRs as the energy source for hydrogen production compared to the current production methods. The benefits include lower greenhouse gas emissions, predictable production conditions and higher total efficiency with cogeneration. The constraints of nuclear hydrogen production are presented in the thesis including the safety point of view, the efficiency issue and lacking infrastructure. SMR powered hydrogen production is lastly applied to industrial settings through a steel industry example. The hydrogen economy is constantly developing, and it is not yet clear how the future looks like in regards of it. The aim of this thesis is to present options for the development direction in the form of combining modern nuclear technologies with modern hydrogen technologies.

Keywords: hydrogen, hydrogen economy, nuclear power, SMRs, electrolysis, fossil-free steel

TIIVISTELMÄ

SMR-teknologiat vedyn tuotannossa

Milla Heino

Oulun yliopisto, Ympäristötekniikan tutkinto-ohjelma

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Tämän kandidaatintyön tarkoituksena on selvittää pienten modulaaristen ydinvoimateknologioiden (SMR-teknologiat) hyödyntämismahdollisuutta teollisuuden tarpeisiin. Työssä esitellään sekä vedyn tuotantotapoja että pieniä modulaarisia ydinreaktoreita. Työn tavoitteen on ollut muodostaa käsitys siitä, miten ydinvoimalla voidaan tuottaa vetyä. Ydinvoimalla tuotetun vedyn tuotantoteknologioiden kehityksen edellytykset ja rajoitukset esitetään työssä. Ydinvoimalla tuotetun vedyn ympäristövaikutuksia verrataan vallitseviin vedyn tuotantomenetelmiin. Työ on toteutettu kirjallisuuskatsauksena.

Ympäristöystävällisten energiantuotantotapojen kysyntä on noussut, kun kasvihuonekaasujen pitoisuudet lisääntyvät ilmakehässä. Energiasektorilla vetytalous on ollut kasvava puheenaihe. Vety on esitetty ratkaisevana tekijänä monissa energiateknologian sovelluksissa. Esimerkiksi, vetypolttokennojen avulla voitaisiin muuntaa liikenne hiilineutraaliksi. Perinteiset vedyn tuotantomenetelmät hyödyntävät fossiilisia polttoaineita, mutta elektrolyysimenetelmiä pidetään tulevaisuuden merkittävimpänä vedyn tuotantotapana. Elektrolyysillä on mahdollista tuottaa melkein puhdasta vetyä ja sitä pidetään ympäristöystävällisimpänä vedyn tuotantomenetelmänä. Vedyn tuotanto elektrolyysillä vaatii kuitenkin paljon energiaa. Tässä kandidaatintyössä ydinteknologiat esitetään fossiilisten polttoaineiden korvaajina energiaintensiivisissä vedyn tuotantoprosesseissa.

Tässä kandidaatintyössä esitellään myös SMR-teknologioiden mahdollisia hyötyjä vedyn tuotannossa verrattuna nykytuotantoon. Hyötyjä ovat muun muassa pienemmät kasvihuonekaasupäästöt, ennustettavissa ja säädettävissä olevat tuotanto-olosuhteet ja korkeampi kokonaistehokkuus yhteistuotannon avulla. Ydinvoimalla tuotetun vedyn rajoitukset, muun muassa turvallisuusnäkökulma ja vaillinainen infrastruktuuri, tuodaan esille. Viimeisenä SMR-teknologiat ja vedyn tuotanto yhdistetään teolliseen ympäristöön terästeollisuuden esimerkin kautta. Vetytalous kehittyy jatkuvasti eikä ole selvää, millaiselta se tarkalleen tulevaisuudessa näyttää. Tämän kandidaatintyön tarkoituksena on esitellä uusia mahdollisuuksia vetytalouden kehittymissuunnalle.

Avainsanat: vety, vetytalous, ydinvoima, SMR-teknologiat, elektrolyysi, vihreä teräs

TABLE OF CONTENTS

SYMBOLS AND ABBREVIATIONS

BF/BOF	The Blast Furnace-Basic Oxygen Furnace
BWR	Boiling water reactor
GHG	Greenhouse gas
GTHR300C	Gas Turbine High Temperature Reactor 300-Cogeneration
HDR	Hydrogen direct reduction
HTE	High-temperature electrolysis
HTTR	High-temperature test reactor
HTGR	High-temperature gas-cooled reactor
MWe	Electric megawatt
MWt	Thermal megawatt
NHP	Nuclear hydrogen production
NPP	Nuclear power plant
NTP	Normal temperature pressure
PEM	Proton-exchange membrane
PWR	Pressurized water reactor
SDG	Sustainable development goals
SMR	Small modular reactor
VHTR	Very high-temperature reactor
VRES	Variable renewable energy sources

1 INTRODUCTION

Rising greenhouse gas (GHG) concentrations in the atmosphere have resulted in changes in the environment's state. For example, the global mean temperature has increased, sea levels have risen, and extreme weather phenomena have become more common. The increase in GHG concentrations is seen as a threat and measures have been taken to limit the GHG emissions to stop global warming (World Meteorological Organization, 2021). United Nations lists 17 sustainable development goals (SDGs) as a part of their 2030 Agenda for Sustainable Development. The purpose of the Agenda for Sustainable Development is to tackle climate change and the loss of biodiversity all while improving social justice and economy. Affordable and clean energy is one of the SDGs listed which highlights the need for environmentally friendly energy production. (The United Nations, 2018)

Finland, as a member of the European Union, has one of the strictest environmental policies in the world (European Union, 2018). The Finnish national Climate act sets objectives for emission reduction in Finland. The aim is for a 60% emissions reduction by 2030 and a 95 % reduction by 2050. According to Suomen virallinen tilasto (SVT), energy production and industrial sources are the main GHG emitters in Finland (SVT, 2019) The Finnish energy sector must undergo multiple changes for Finland to reach its emission reduction targets. (Ministry of the Environment, n.d.)

As the share of variable energy sources (VRES) increases in power grids, energy storage capacity must increase as well. Hydrogen economy and hydrogen itself have been listed as prospective solutions to combat climate change by enabling a more flexible energy system. The increasing interest in hydrogen has led to a new wave of development. Hydrogen-based energy systems are expected to provide low emission energy supporting national and worldwide decarbonization goals. However, several constraints hinder the development and commissioning of hydrogen-based energy systems. The market for hydrogen is not fully developed yet and construction of the infrastructure required for hydrogen economy has high costs. In addition, hydrogen possesses characteristics that hamper the development. For example, hydrogen has a high diffusivity and explosivity, requiring sophisticated storage and transportation solutions. (Choudhuri & Gollahalli, 2000; Gandía et al., 2013)

Even though the chemical energy in hydrogen can be transformed into electricity via fuel cells, hydrogen itself it is not classified as a fuel; hydrogen is an energy carrier whose production requires other sources of energy. Current hydrogen production technologies mainly utilize non-renewable energy sources e.g., natural gas, coal and nuclear power. The predicted growth of VRES in the power grids requires a significant growth in hydrogen production and hydrogen storage. Even though nuclear power is classified as a non-renewable energy source, when compared to other non-renewable energy sources, nuclear power provides relatively low emission energy. Hydrogen production using nuclear power is called nuclear hydrogen production (NHP). Small modular nuclear reactors and especially high-temperature gas cooled reactors (HTGRs) are presented as a feasible reactor type for nuclear hydrogen production. The development of NHP systems aims to increase the total efficiency of the process through cogeneration of variating end products. (Gandía et al., 2013; IAEA, 2018)

The goal of this thesis is to investigate the possibility of utilizing SMRs in providing nuclear hydrogen for industrial needs. Through a literary review the feasibility and environmental perspective of nuclear hydrogen production is assessed. Different hydrogen production technologies are presented and compared highlighting the environmental impacts. Furthermore, NHP technologies are compared to traditional hydrogen production technologies. Lastly, nuclear hydrogen production is presented as an option in the steel industry's transformation towards decarbonization by applying SMR powered hydrogen production to the HYBRIT project. The HYBRIT project is funded by multiple steel companies and the goal of the project is to develop a fossil-free production technology for steel through hydrogen reduction. (SSAB et al., n.d.-a)

2 HYDROGEN PRODUCTION

The Paris agreement, adopted in 2015 by almost 200 countries, it is a legally binding environmental treaty. The aim of the treaty is to limit the increase of the global average temperature to 1.5°C, maximum 2°C, compared to pre-industrial times. The countries that signed this treaty have all agreed to reach climate neutrality in regards of CO_2 emissions by 2050 (UNFCCC Secretariat, 2016). To achieve climate neutrality, rapid changes are needed in the current energy systems. These changes can already be seen globally as the share of renewable energy production has increased significantly in the last decade. For example, renewable energy sources like photovoltaics and wind turbines have become more popular in energy systems since their cost-effectiveness has increased. These redundant technologies are important in the future development of energy production, but it is recognized that hydrogen can play a big role in the fight against climate change. Therefore, hydrogen is one of the key factors in achieving the goals of the Paris agreement. (Brigljević, et al., 2022; Reigstad et al., 2022)

Renewable energy production is an important part in the decarbonization of energy systems. With renewable energy sources the production rate depends on the time of day, season and the occurring weather. These energy sources are referred to as variable renewable energy sources. Fluctuations cause network stability and energy security issues in the grid; consequently, the increase of renewable energy production increases demand for energy storage solutions, as energy storage technologies increase load control, flexibility and resilience in the electrical grids. This is where hydrogen comes into the picture. Hydrogen is high energy intensity energy carrier, and it is therefore considered a potential candidate for load controlling in the future. Load controlling allows the total power consumption to be distributed over time which reduces the gap between demand and supply. Energy storages enable peak shaving. (Brigljević, et al., 2022; Gandía et al., 2013; Karmiris & Tengnér, 2013)

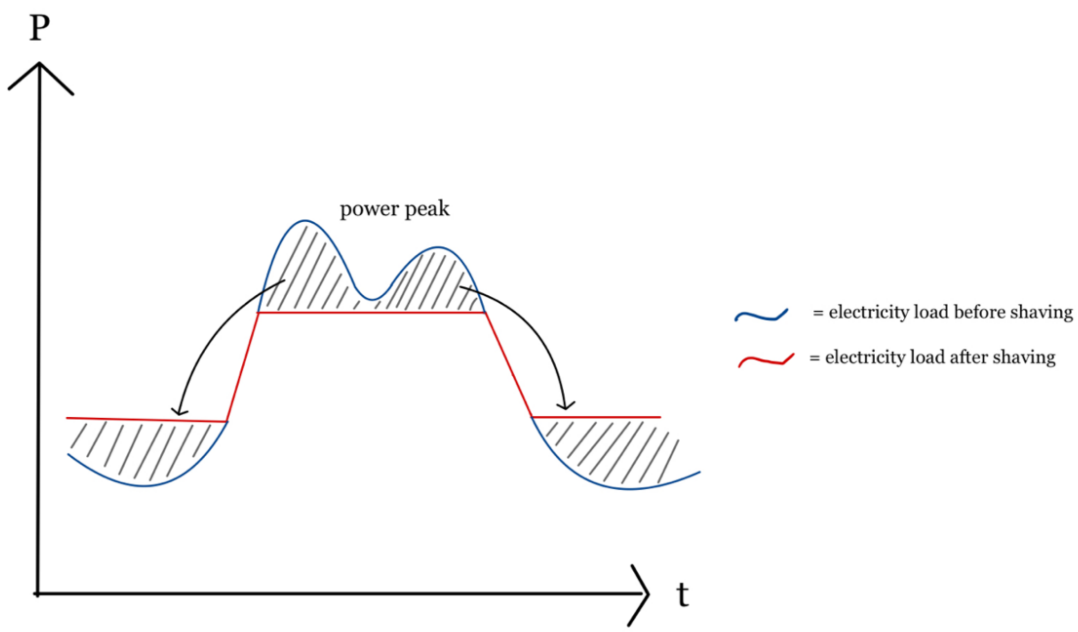

Figure 1: Peak shaving principle. In accordance with **(Karmiris & Tengnér, 2013)**

Hydrogen is not a totally unknown resource for existing industries. It is commonly used in chemical and petrochemical processes. Oil refining and ammonium syntheses are traditional uses of hydrogen. It is speculated that in the future hydrogen will be used not only as a load controller but in transportation and fuel cells as a power source (Gandía et al., 2013). The importance of hydrogen is recognized as well by The Ministry of Economic Affairs and Employment of Finland. The Ministry states in their climate and energy strategy that hydrogen is a part of flexible energy use and the decarbonization of industries. It is highlighted in the strategy that, for Finland to fulfill the carbon neutrality goals, it is necessary to use hydrogen in increasing amounts. The development of hydrogen production methods and the infrastructure around it is required in the transformation of highly emissive industrial processes to carbon neutral ones. (Lintilä, 2021)

2.1 Properties of hydrogen

Hydrogen is the first and lightest element on the periodic table with a relative atomic mass of 1.008. In addition, it is the most abundant element in the universe. On Earth hydrogen is commonly found in water and in the atmosphere. The concentration of hydrogen in water is greater than the concentration in the atmosphere. Even though hydrogen is one of the most abundant elements on Earth, right after oxygen and silicon, it is bonded to other components (Tapani Raunio, 2005). Most often hydrogen forms hydrocarbons with carbon and water with oxygen (Koponen, 2020). Hydrogen has a heating value of 119 MJ/kg which is approximately 2.7 times larger when compared to for example gasoline (MAOL, 2019). However, to utilize this high energy content, energy needs to be spent to separate H_2 from the compounds it is a part of. Because of this reason, hydrogen is not considered a primary energy source but rather an energy carrier. (Choudhuri & Gollahalli, 2000; Jääskö, 2021; Royal Society of Chemistry, 2011)

Hydrogen is seen as a crucial part of the post-energy-transform power grids. It has the potential to not only store energy to balance out the peaks of power demand but also work as a fossil-free transportation fuel (Andersson & Grönkvist, 2019). Even though hydrogen is considered safe from an environmental perspective for it only produces water when reacting with oxygen, some of its characteristics create additional restraints to the development of, especially, storage and transportation technologies. Because hydrogen has a small molecular size, its diffusivity is high. Hydrogen has the possibility to leak from industrial processes to surrounding air through valves, seals and even pipelines and containers. When mixed with air in confined spaces, hydrogen creates a mixture that is explosive if ignition occurs. Explosiveness poses a risk for hydrogen use. When it comes to the storage of hydrogen, its low density in gaseous form under normal conditions significantly increases the volume needed for storage. One kilogram of hydrogen takes up 11 m^3 in NTP-conditions. For the storage of hydrogen to be reasonable economically, the storage density must be increased. (Andersson & Grönkvist, 2019; Diáguez et al., 2013).

2.2 Hydrogen production technologies

Currently, there is not an existing consensus on which one of the hydrogen production methods should be preferred. All the hydrogen production technologies face some form of economic, environmental, and technological hardships. Hydrogen production technologies are divided into nonrenewable and renewable production technologies. The pathways for renewable hydrogen are presented in figure 2 and the pathways for nonrenewable hydrogen are presented in figure 3. As seen in the figures, the division is based on the energy source used in the production process. The actual production technology does not impact the classification which means that one production technology can be classified as renewable and nonrenewable depending on the primary energy source. Renewable production technologies can consequently produce CO_2 emissions as well. (Gandía et al., 2013; Kayfeci et al., 2019; Tapani Raunio, 2005)

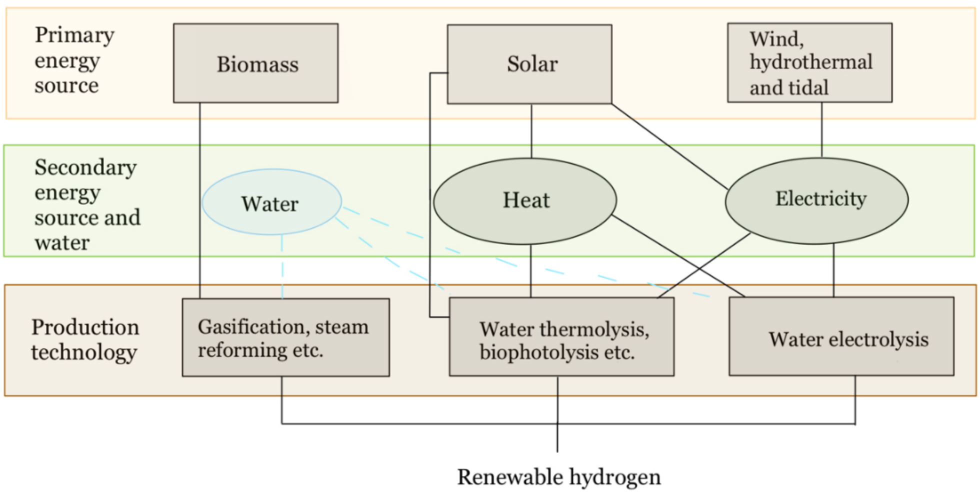

Figure 2: Renewable hydrogen pathways. In accordance with (Kayfeci et al., 2019)

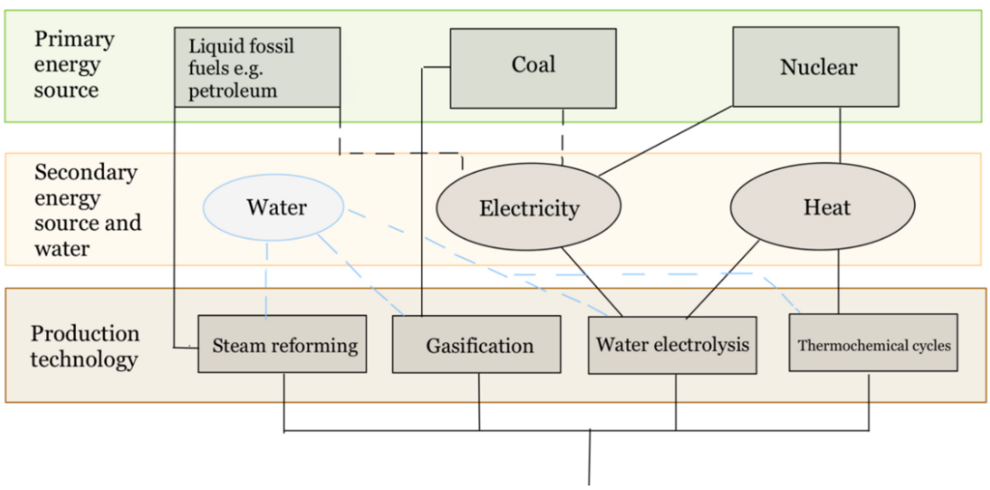

Figure 3: Nonrenewable hydrogen pathways. In accordance with (Kayfeci et al., 2019)

Almost all the hydrogen produced in the world is through nonrenewable production technologies. At the moment, the most prevalent technology is steam methane reforming. The popularity of steam methane reforming is based on the cost-effectiveness of the process. The cost of the production is linked to the development level of the technology as well as the existing infrastructure for the production. There is however an interest in developing other technologies since steam methane reforming produces GHG emissions and is not considered environmentally friendly. Other promising hydrogen production technologies are in the research and development phase and their final cost in industrial scales remains unknown. (Gandía et al., 2013; Kayfeci et al., 2019; Tapani Raunio, 2005)

2.2.1 Steam methane reforming

Approximately 99 % of the world's hydrogen production is carried out by steam reforming and gasification of fossil fuels. In Europe, it is estimated that approximately 95% of hydrogen is produced by steam methane reforming. Steam methane reforming is a cost-efficient way of producing hydrogen from natural gas and the technologies are mature. (Cihlar et al., 2020; Hydrogen and Fuel Cell Technologies Office, n.d.; Jääskö, 2021; Tapani Raunio, 2005)

In steam methane reforming, methane reacts with water in high temperatures. Reacting in 500-800°C, methane and water produce hydrogen, carbon monoxide and carbon dioxide by following endothermic chemical reactions.

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

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (2)$$

The carbon monoxide produced in the reaction reacts further with water by a so-called shift reaction producing carbon dioxide and hydrogen.

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

A nickel catalyst is often used in steam methane reforming processes to increase the reaction velocity. The ideal conditions for steam methane reforming are a temperature within 700 to 800°C and a pressure of 3-25 bar in the methane steam stream. The high temperature can be acquired from industrial processes that produce great amounts of excess heat. (Hydrogen and Fuel Cell Technologies Office, n.d.; Tapani Raunio, 2005)

2.2.2 Water electrolysis

Water electrolysis is a technology used to produce hydrogen from water. Water electrolysis is based on a phenomenon called water splitting. The chemical reaction for the water splitting in water electrolysis is following in standard conditions of 298 K and 1 bar. (Millet & Grigoriev, 2015)

$$H_2O_{(l)} \rightarrow H_{2\,(g)} + \frac{1}{2}O_{2\,(g)} \qquad (4)$$

In water electrolysis, water is the input of the process. Water splitting, which means the separation of hydrogen from water, is induced by electricity. Hydrogen is reduced in the electrolyzer's cathode, and the oxygen is oxidized in the anode. Water splitting can occur in variating temperatures and the water electrolysis technologies are often divided based on the temperature in the process. Low-temperature electrolysis happens in temperatures below 150ºC. Medium-temperature electrolysis occurs in temperatures between 200ºC and 600ºC. High-temperature electrolysis takes place in temperatures over 600ºC. In figure 4, a principle picture of a water electrolyzer is presented. (Millet & Grigoriev, 2015)

Water electrolysis can be further divided in to three main technologies: alkaline water electrolysis, proton-exchange membrane water electrolysis (PEM-electrolysis) and high-temperature water electrolysis. Water electrolysis is possible in acidic water as well. However, alkaline electrolyzers are more commonly used since the acid water electrolyzers face a plethora of issues with corrosion. All the electrolyzers construct of two metallic electrodes, cells in which the electrolysis takes place and a membrane that separates the electrodes. The separating membrane prevents the recombination of H_2 and O_2. The two electrodes, anode and cathode, are submerged in an electrolyte. The materials and electrolyte liquids used in electrolyzers vary depending on the electrolysis technology. In addition to the materials varying, the process parameters change as well. (Jääskö A, 2020; Millet & Grigoriev, 2015)

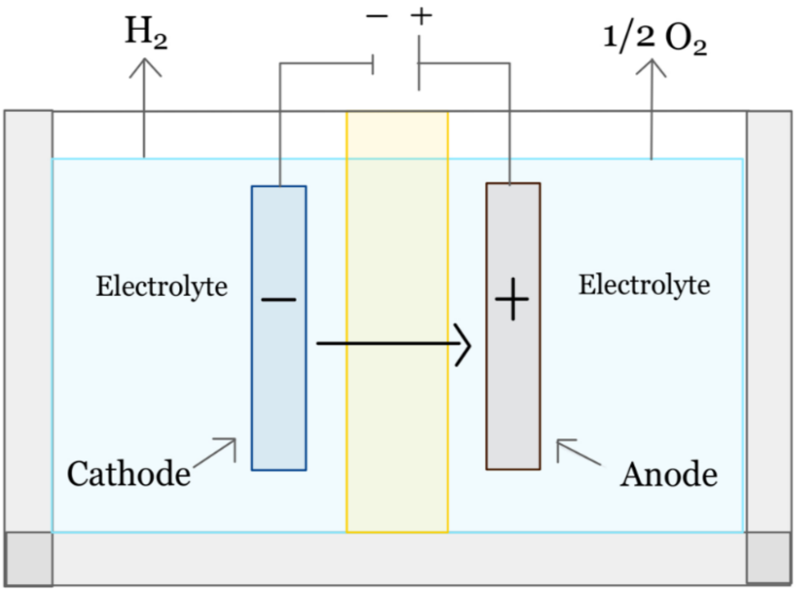

Figure 4: Principle picture of alkaline electrolysis cell. In accordance with (Millet & Grigoriev, 2015)

2.2.3 Other technologies

In addition to steam methane reforming, other fossil fuels such as coal can be used to produce hydrogen. In fact, coal gasification is the oldest method in hydrogen production. Gasification is a multi-phase process including the actual gasification in a high temperature (900ºC) which produces a synthesis gas composing of carbon monoxide, hydrogen and ash. The gasification commonly takes place in large reactor vessels. In the vessel, coal reacts with oxygen and high-temperature steam. Since the product is a combination of different components, hydrogen needs to be separated from the product stream. The carbon monoxide in the synthesis gas reacts with water in a shift reaction and produces carbon dioxide and hydrogen. To produce pure hydrogen gas, the synthesis gas stream requires purification. The classical gasification process of coal is presented in figure 5. (Kayfeci et. al, 2019)

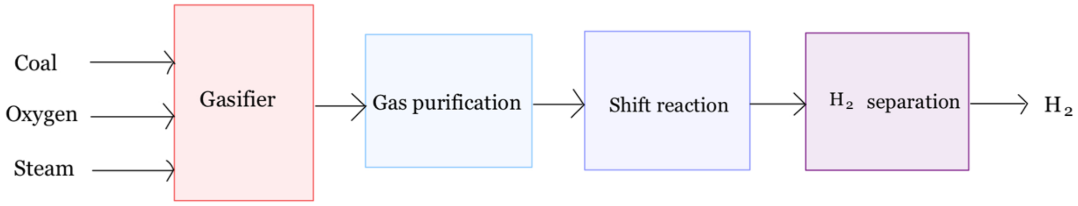

Figure 5: Process chart of coal gasification. In accordance with (Kayfeci et al., 2019)

Biomass resources, for example urban waste and wood industry residues, can be used in a similar way as fossil fuels to produce hydrogen. This is called biomass gasification. When biomass is gasified in high temperatures a multicomponent mixture is formed. The multicomponent mixture is gaseous and contains hydrogen, carbon monoxide, carbon dioxide, methane and impurities such as hydrocarbons and charcoal. Similar to the gasification of coal, the gas stream needs purification in order for pure hydrogen to be captured. Biomass gasification forms a great amount of impurities which is considered an issue in hydrogen production. (Jääskö, 2021; Kayfeci et al., 2019)

Thermochemical cycles are a technology used to produce hydrogen by combining water, chemicals and heat. Hundreds of thermochemical cycles have been developed. The most common thermochemical cycle is an iodine-sulfur cycle. In iodine-sulfur cycle, water is added to a mixture of iodine and sulfur dioxide. The reaction forms, among other compounds, hydrogen iodide which can be further distillated to separate the hydrogen and iodine from each other. The reactions are presented in equations 5 and 6. Iodine-sulfur cycle does not produce carbon dioxide, but it requires multiple phases since the wanted product, hydrogen gas, as well as the iodine, sulfuric acid and sulfur dioxide must be recovered from the product stream. (Jääskö, 2021; Tapani Raunio, 2005)

$$SO_2 + 9I_2 + 16H_2O \rightarrow 2HI + 8I_2 + 10H_2O + H_2SO_4 + 4H_2O \quad (5)$$

$$2HI \rightarrow I_2 + H_2 \quad (6)$$

The reaction in equation 5 does not require a high reaction temperature. However, the separation of the wanted products requires high temperature conditions. The high temperature of the separation process has an impact on the efficiency of the whole process. (Jääskö, 2021; Tapani Raunio, 2005)

2.3 Environmental impacts of hydrogen production

The future of hydrogen production is unclear. The concept of hydrogen economy is under development and there are several contrasting opinions on what it will look like. In multiple instances hydrogen is highlighted as a key factor in the energy systems of the future (Koponen, 2020). On the contrary, there is a so-called efficiency issue when it comes to hydrogen production with renewable energy sources. The efficiency issue arises from the difference between the electricity used to produce hydrogen and the electricity obtained from hydrogen. When hydrogen is produced with water electrolysis using renewable energy sources, it is estimated that only one fourth of the electricity is available from the hydrogen's chemical form after the production and storage phase. This difference has led to the conclusion that hydrogen production with VRES is inefficient and therefore unreasonable and it would be more beneficial to use the electricity directly and not convert it to hydrogen. It is argued as well that an inefficient process cannot be a sustainable one. A high-temperature electrolysis (HTE) is one of the solutions presented to fight the efficiency issue of hydrogen production. In HTE, the electricity needed in the process decreases as the temperature of the steam directed to the electrolyzer increases. High-temperature nuclear reactors have been presented as a possible source for this high temperature steam. (Gandía et al., 2013)

The development of hydrogen production methods and hydrogen use has received attention and funding during recent years (Lintilä, 2021). At the moment, 96% of the hydrogen produced is classified as grey hydrogen. Hydrogen is often classified using color codes to separate different types of hydrogen (Panić et al., 2022). The color codes of hydrogen are presented in figure 6. The only technologically and economically profitable production method of hydrogen in industrial scale is steam methane reforming from natural gas. Though steam methane reforming is the current predominant technology, it is predicted that in the future the share of water electrolysis powered by renewable energy sources in hydrogen production will increase. This is mainly due to strong environmental policies. Steam methane reforming does not produce hydrogen as pure as electrolysis technologies. In addition, GHG emissions are formed in traditional hydrogen production processes. CO_2 is a greenhouse gas, and it is seen as the largest contributor to climate change (Lindsey, 2022). Even though the GHG emissions can be captured from the product stream with carbon capture, utilization and storage technologies, the captured emissions need to be permanently stored which increases the cost of production. (Gandía et al., 2013; Kayfeci et al., 2019; Panić et al., 2022; Reigstad et al., 2022)

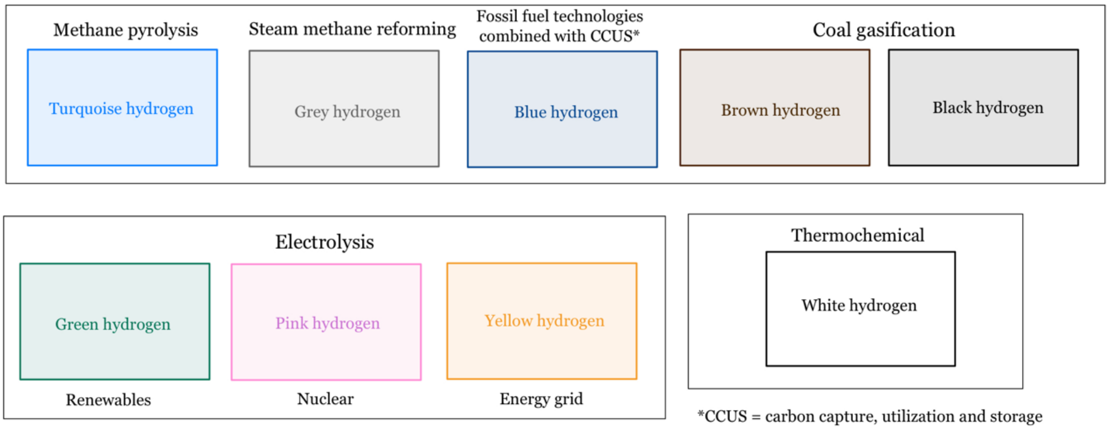

Figure 6: Hydrogen color codes. In accordance with (Panić et al., 2022)

Compared to steam methane reforming from natural gas, water electrolysis using renewable energy sources can be seen as more environmentally friendly. Water electrolysis product steam consists only of water and hydrogen, whereas other hydrogen production technologies produce GHG emissions. Only 4 % of hydrogen is produced with electrolysis technologies. If the hydrogen production industry were to be carbon neutral, water electrolysis capacity would need to be increased by 100 % (Koponen, 2020). When looking at the bigger picture, even though electrolysis technologies using renewable energy sources do not produce GHG emissions, some aspects of the production can contribute to the environment in a negative way. Electrolysis cells contain electrodes that consist of different metals e.g., platinum and nickel that require mining. Mining causes disorder in the natural environment which affects both wildlife and humans negatively. The negative impacts of mining have been under scientific discussion for a relatively long time (Thornton, 1996). Another significant issue in sustainability of water electrolysis is water itself. In some regions water is a scarce resource. Therefore, in these regions it may not be sustainable and environmentally reasonable to produce hydrogen with water electrolysis. (Gandía et al., 2013; Jääskö, 2021)

3 SMALL MODULAR NUCLEAR REACTORS

In nuclear power plants (NPPs), power is produced with fission reactions. Fission reaction is a reaction where the nucleus of an atom splits. Nuclear fuel consists of uranium. When neutrons are directed to nuclear fuel, a fission reaction happens in the nucleus of uranium atoms. The reaction releases heat, neutrons and radiation. The released neutrons cause splitting in the surrounding atoms and create a chain reaction that enables a continuous power production. In nature, uranium-238 is more abundant than uranium-235 however it is not as prone to nuclei splitting as uranium-235 isotope. Therefore, the concentration of uranium-235 is enriched in nuclear fuel to ensure the chain reaction. The heat released in the fission reaction is transformed into electricity in steam turbines in traditional NPPs. (Patterson, 1982)

Ever since nuclear power has been produced, the focus has been on traditional NPPs since the economy of scale benefits the building of a large power plant (Nuclear Energy Agency, 2011). Conventional NPPs have reactors that produce more than 700 MWe (Liou & IAEA, 2021). The highest power produced by a singular nuclear unit is 1660 MWe. The pressurized water reactor (PWR) is the most common reactor type in the world. When combined, PWRs produce 66 % of nuclear power in the world. The second most common reactor type is a boiling water reactor (BWR). BWRs cover for 16 % of the world's nuclear power production (Ho et al., 2019). Besides these traditional NPPs, new kind of reactor type is arising. Nuclear accidents and delays in the building phases of large nuclear units have made it compelling to create new reactor designs that are safer and do not require significant capital investments. These new reactor designs are called small modular nuclear reactors. The classification of the term SMR is still inconsistent since SMR technologies are in their development phase. Examples of prospective SMR designs and names are introduced in figure 7. SMRs are nuclear reactors with effective electrical power of maximum 300 MWe. Compared to the traditional NPPs they are considered more versatile. They could potentially be used in the generation of high temperature steam for industrial needs or as a power source in remote areas. SMRs could aid in load following and enable efficient production of hydrogen. (Ho et al., 2019; IAEA, 2018; Nuclear Energy Agency, 2011)

SMR designs									
	USA	Russia	Japan	France	India	South Korea	Argentina	China	Italy
Integral PWR	IRIS		IMR	SCOR		SMART	CAREM		
	NuScale								
	mPower								
BWR/PHWR		VKR-MT	CCR		AHWR				MARS
Gas-cooled	GT-MHR	BGR-300	GT-HTG-300					HTR-PM	
Pb-Bi cooled	ENHS	BREST	LSPR						
	STAR/SST	SVBR-100							
	AR	SVBR-75							
Sodium-cooled	PRISM	BN-GT-300	4S			KALIMER			
	ARC-100		RAPID						
Non-conventio	AHTR	MARS	MSR-FUJI		CHTR				
	Hyperion								
	TWR								

Figure 7: Current SMR designs. In accordance with (Vujić et al., 2012)

When it comes to the basic principle of producing nuclear power, SMRs and traditional NPPs are alike. Even though the energy production principle is the same, SMRs and traditional NPPs have other significant differences. Rather than building the power plant completely on site, SMRs are designed to be constructed modularly in a factory. The modularization of SMRs means dividing the power plant into small sub-systems. The separate systems are designed in a way that they all have an individual purpose but do not greatly impact other systems. Since SMRs are smaller in size than traditional NPPs, the transportation of the separate systems is possible. The sub-systems create an SMR module after combined. Multiple SMR modules can be linked to increase the power capacity of the power plant. The physical size of an SMR module limits its power production capacity to 300 MWe. Modularity in the SMR designs decrease maintenance costs since individual components can be changed without having to replace whole systems. (Galindo & IAEA, 2022; Ho et al., 2019; Hussein, 2020; Liou & IAEA, 2021; Nuclear Energy Agency, 2011)

Other differences when comparing traditional NPPs and SMRs are the safety features. The aim of SMRs from the safety point of view is to only rely on inherent and passive safety features. The philosophy behind passive and inherent safety features is that the risk of reactor core damage accident is not controlled but rather avoided. Passive safety features function without external power sources since they are based on physics and natural phenomena. One of the most important inherent safety features is a negative reactivity coefficient. Negative reactivity coefficient means that if the temperature of the reactor core is increased or reactor coolant is lost, the power of the reactor decreases. Traditional NPPs use passive safety systems but they use active safety systems as well.

Active safety systems require external power to function. The smaller size of SMRs increases the effectivity of both inherent and passive safety features. (Hussein, 2020)

Other passive safety features that are included in SMR designs are natural convection, natural circulation and gravity-driven control rods. Natural convection is used in decay heat removal circuits in many of the SMR designs. Decay heat occurs in nuclear reactors when the radioactive materials continue to split after the reactor is shut down (Raj, 2015). Natural convection is often enhanced with gravity assisted circuits. Gravity is also used to drive down the control rods in the reactor core. Control rods reduce the amount of fission reactions by absorbing neutrons in the reactor pressure vessel. Natural circulation in SMRs is used to keep the reactor core temperature down. Natural circulation is based on the phase transformations of liquid water when it is used as a moderator. Moderator is the material used to slow down neutrons in the reactor. (Hussein, 2020; IAEA, 2005, 2018; Nuclear Energy Agency, 2011)

Some problems have been stated concerning the passive safety systems in SMRs. There is not as much user experience from passive safety systems than active ones which makes them less predictable and therefore less reliable. It may be challenging to control passive safety systems and the lack of experience makes it harder to predict the simultaneous co-existence of the two safety system types. However, the development of SMRs aims to decrease the risk of large-scale nuclear accidents with passive safety features. The increased safety in SMRs could enable industrial use. The size of SMRs makes them suitable for a wide range of utilization purposes. Traditional NPPs are designed to mainly produce electricity whereas the possibilities for SMRs are still open. It is possible to generate heat, utilize nuclear waste, cogenerate heat and electricity and produce hydrogen with applied SMR technologies. Since the initial cost of SMRs is significantly smaller than that of conventional NPPs, it is possible for smaller companies to make the investment and benefit from low carbon emitting nuclear power. (Hussein, 2020; IAEA, 2018)

3.1 SMRs for hydrogen production

Due to the status quo of the environment, the utilization of renewable energy sources is highlighted in the development of hydrogen production technologies. In multiple hydrogen production methods, high temperatures are required. High temperatures can be produced with electricity from renewable and non-renewable energy sources. Nuclear power is considered a potential energy and heat source for hydrogen production as well. Climate incentive supports the use of nuclear power since only low levels of CO_2 are released during the production of nuclear power. Compared to renewable power sources, with nuclear power not only electricity but high temperature steam could be generated for hydrogen production. High temperatures decrease the amount of electricity needed in water electrolysis and the production of direct heat is more cost-effective since the general cost of heat is lower than the general cost of electricity. All the main technologies of hydrogen production, steam methane reforming, thermochemical cycles and water electrolysis, could be combined with high temperature nuclear technologies. These technologies are still in the development phase nevertheless they are considered promising regarding the future of hydrogen production. (Gandía et al., 2013; Millet & Grigoriev, 2013; Petrunin et al., 2020)

For nuclear hydrogen production the emphasis of the development has been on high temperature gas cooled reactors. HTGRs are classified as SMRs. HTGRs reactor core is composed of graphite. Graphite has a high heat resistance which makes it a suitable material for the high temperatures present in the reactor. An inert helium gas is used as a coolant in HTGRs to avoid chemical reactions in the reactor core. HTGRs are considered safe for industrial use since the design inherently prevents the release of radioactive materials. (Yan et al., 2013) Very high temperature reactor (VHTR) is one conceptual design of a HTGR. There is one operating VHTR in the world and it is the high temperature test reactor (HTTR) in Japan. It has a thermal output of 30 MWt. The HTTR has been used to further develop HTGR designs. HTTR, as a nuclear thermal power source, could be connected to a thermochemical iodine-sulfur-cycle that produces hydrogen. Thermochemical cycles require higher temperatures than water electrolysis and therefore other HTGR designs with a lower outlet temperature than the HTTR would be more suitable for HTE systems. (Inagaki et al., 2012; McKellar et al., 2010)

Figure 8 presents the conceptual design of a Gas Turbine High Temperature Reactor 300-Cogeneration (GTHR300C) system. GTHR300C is a NHP system that is based on HTGR and combined to an iodine-sulfur process. In the design, a gas turbine and a generator are also connected to the reactor to enable cogeneration of electricity. The reactor core has a simplified design: the fuel rods are held together with a central graphite rod. Simplicity in the core design has multiple benefits. For example, the fuel burnup and power density are increased. A heat exchanger in the system enables safe heat transfer to the turbine and hydrogen production plant. (Yan et al., 2013)

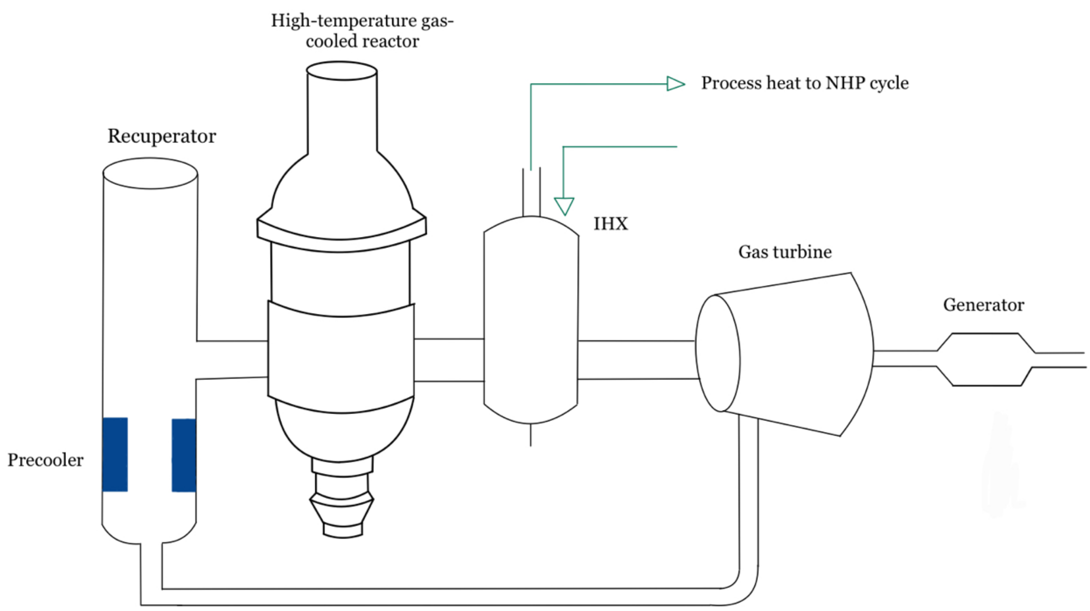

Figure 8: GTHTR300C system design. In accordance with (Yan et al., 2013)

Figure 9 shows a concept for a HTE system powered by an HTGR. The high temperature from the reactor increases the efficiency of electrolysis hydrogen production. In the NHP process, the helium coolant works as a heat conveyer and as the working fluid in the gas turbine. Helium is used to transfer heat from the reactor core to the HTE plant through a heat exchanger. (O'Brien, n.d.)

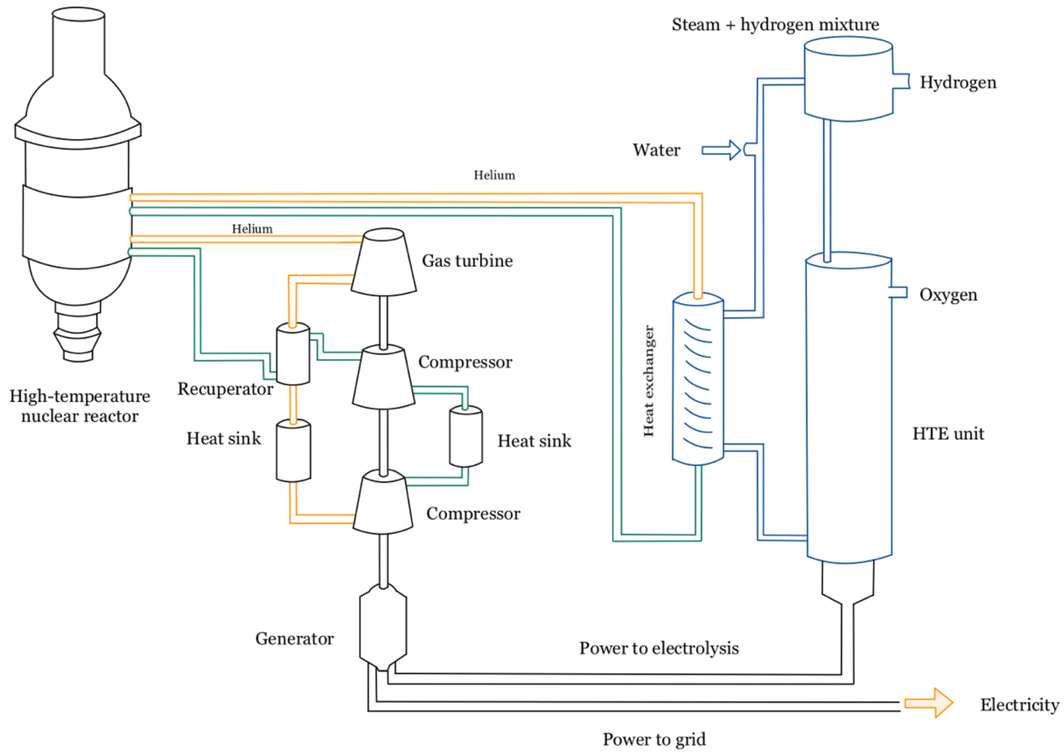

Figure 9: High-temperature reactor combined to a HTE unit. In accordance with (O'Brien, 2010)

Several factors impact the conclusion outcome when comparing the two presented NHP technologies. When nuclear power is combined with thermochemical cycles the production cost of hydrogen is lower than with HTE. However, iodine-sulfur processes face a problem with corrosion in the system since sulfuric acid and hydrogen iodide are present. The need to control three separate chemical reactions complicates the system design as well. The efficiency of HTE and thermochemical cycles is on the same level. NHP with HTE does not require anti-corrosion technologies which simplifies the system design. In addition, HTE is not dependent on fossil fuel consumption since the process input is water. GHG emissions are not released in nuclear HTE which makes it superior to other hydrogen production technologies from the environmental perspective. (Inagaki et al., 2012; O'Brien, n.d.)

3.1.1 Cogeneration plants

The cost of electricity varies during the day. When the cost is low, the production of other end products can be more valuable. In cogeneration plants, the products are alterable. For example, with HTGRs, the end product could be high temperature steam, electricity or hydrogen. The high temperatures formed in HTGR reactors are not only suitable for hydrogen production purposes. Other industrial processes require high temperature steam as well. HTGR designs hold a very low risk of radioactive material release from the reactor core which opens a variety of possibilities for areas of use. For example, SMRs are mentioned as a potential heat source for district heating. Cogeneration can increase the effectivity of the nuclear power plants. Cogeneration of electricity and heat makes the process more economical since larger proportion of the produced nuclear heat is utilized. It is estimated that with cogeneration of nuclear hydrogen and electricity, high efficiency rates can be achieved. In a cogeneration plant where hydrogen is one of the products, it is beneficial to optimize the outlet temperature of the SMR in regards of the hydrogen production technology. Thermochemical cycles reach a higher thermal efficiency when the outlet temperature of the reactor is lower whilst HTE is more thermally efficient when the outlet temperature is higher. (Dudek et al., 2016; Locatelli Giorgio et al., 2018; Yan et al., 2013)

3.2 Environmental impacts of nuclear hydrogen production

According to life cycle analyses, NPPs GHG emissions fall between non-renewable fossil fuel powered energy and renewable energy. When assessing the GHG emissions released during the lifetime of SMRs, not only the operational and maintenance phase are considered. Uranium mining and enrichment, construction and decommissioning phase of the power plant must be accounted for to get a descriptive assessment. As seen in figure 10, when comparing SMRs to non-nuclear power plants life cycle GHG emissions, nuclear power plants are clearly less emitting. Even though renewable energy sources are generally considered better for the environment than nuclear technologies, the levelized cost of electricity with renewable energy sources is not yet competitive which slows down the large-scale commissioning. With the traditional NPPs the capital cost has discouraged the wide integration of nuclear power to electrical grids. SMRs anticipated lower initial cost offers new possibilities as a transitional option between non-renewable and renewable power sources. Emission regulation steers the cost-effectiveness of energy production. Therefore, in the future, as emission regulations become stricter, SMRs are a viable option since the levelized cost of electricity is equivalent with nonrenewable energy sources. (Carless et al., 2016)

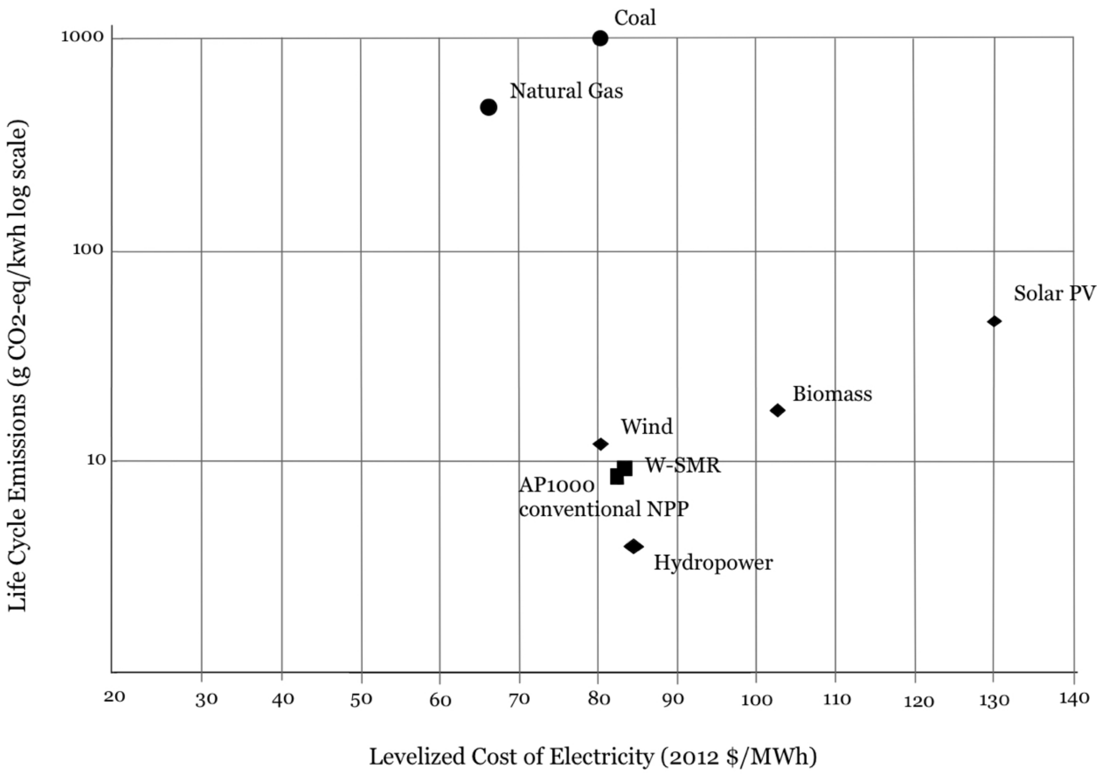

Figure 10: The levelized cost of electricity. In accordance with (Carless et al., 2016)

4 HYDROGEN-BASED STEELMAKING WITH NUCLEAR POWER

European Union is set out to achieve climate neutrality by 2050. The regulations considering GHG emissions are therefore becoming gradually stricter in the future. Tightening regulations increase production costs of high emitting industries. For example, the steel industry produces nearly 6 % of EU's GHG emissions. However, steel import is a significant economical factor for the European Union. To prevent steel companies from relocating their production to less regulated areas, new cost-effective and environmentally friendly production methods of steel are required. The blast furnace/basic oxygen furnace (BF/BOF) process is currently the most common process for steelmaking. In the BF/BOF process, coking coal i.e., coke is used as the main fuel for the process. It functions as the reducing agent and reduces the iron ore in high temperatures. (Haapakangas, 2016; Rübbelke et al., 2022; Vogl et al., 2018)

To decarbonize the steel industry, fundamental changes are required in manufacturing processes. Therefore, a new reducing agent has been introduced: hydrogen. Hydrogen direct reduction process (HDR) is considered a strong candidate for fossil free steel manufacturing. HDR offers a more environmentally friendly production method than the conventional BF/BOF process. Taking into consideration both economic and environmental factors, hydrogen direct reduction is seen as the most feasible technology in the future. Even though the potential of hydrogen direct reduction has been recognized, only a few process designs and their performance have been studied. A design for an HDR process is presented in figure 10. (Rübbelke et al., 2022; Vogl et al., 2018)

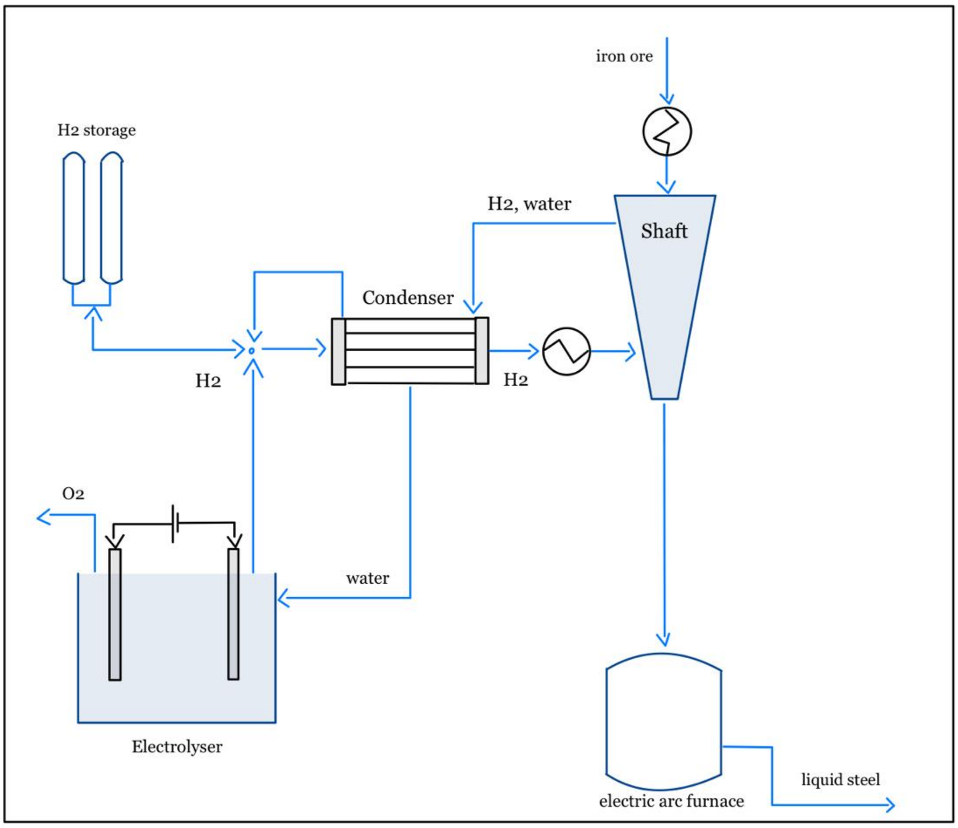

Figure 10: Hydrogen direct reduction in steel manufacturing. In accordance with (Vogl et al., 2018)

Hydrogen direct reduction has gotten attention from big steel companies. For example, SSAB, LKAB and Vattenfall established the HYBRIT project in 2016. The HYBRIT project' mission is the development and research of HDR. The integration of HDR process to steel manufacturing decreases CO_2 emissions since HDR powered by renewable energy sources only creates water vapor emissions. The research and development process has led to the building of an experimental direct reduction plant to Luleå, Sweden. The demonstration plant utilizes renewable energy electrolysis technologies to produce hydrogen for iron ore reduction. The demonstration plant is estimated to produce approximately 1.2 million tons of crude steel a year which accounts for one fourth of Sweden's steel production. With the mentioned production rate, 14.3 million tons of CO_2-eq GHG emissions can be avoided in a time frame of 10 years. (SSAB et al., n.d.-b, n.d.-a)

Since electrolysis powered with renewable energy is considered fossil-free, the HYBRIT project aims to use wind and waterpower to supply the electrolyzers with electricity. Thermochemical cycles and steam methane reforming are options for hydrogen production as well, but the climate incentive favors electrolysis even though it is an energy intensive process. One advantage of electrolysis is that it produces pure H_2 gas compared to other hydrogen production technologies. The HDR process requires pure H_2 gas. The economic viability of hydrogen production via electrolysis is highly dependent on the cost of electricity. The use of renewable energy faces an issue when it comes to intermittency. If renewable energy is not available during the production time frame, non-renewable energy might have to be used for hydrogen production which causes CO_2 emissions. Currently, there are no existing designs for NHP plants for the steel industry. However, SMRs can produce power in a more stable and predictable way than VRES. In addition, especially HTGRs are seen as a prospective method to lowering the cost and greenhouse gas emissions of hydrogen production which is why nuclear technologies may be worth considering for the needs of the steel industry as well. (Krüger et al., 2020; McKellar et al., 2010; Petrunin et al., 2020)

5 CONCLUSION

Environmental policies are directing the development in the energy industry. In the Paris agreement, targets are set out with the objective to reduce GHG emissions promptly. Aiming at climate neutrality, the Finnish energy grids is undertaking a process of decarbonization. The change can be perceived for example in the rising share of renewable energy production. However, common renewable energy sources e.g., photovoltaic and wind turbines, have a weather dependent power production scale. The fluctuation in power production creates issues in the prevalent power grids. As a solution for the issues, hydrogen economy has been presented. Hydrogen storage could enable the integration of VRES into power grids at larger amounts. Hydrogen can be produced with carbon neutral production technologies making the fulfilment of Paris agreement climate policies possible. However, our energy grids and infrastructure are not yet completed for a large-scale hydrogen economy and further development is required. Hydrogen has a high diffusivity which makes it possible to leak from industrial processes making it a safety hazard if development especially in hydrogen storing is not adequate.

Hydrogen production technologies are classified either as non-renewable or renewable. The classification is based on which energy source is used in the process. Non-renewable hydrogen production technologies account for 99% of hydrogen production. Currently, steam methane reforming is the leading production technology. Other technologies include water electrolysis, gasification and thermochemical cycles. Since the prevalent technology, steam methane reforming, produces GHG emissions, the direction of hydrogen economy development focuses more on water electrolysis technologies. Hydrogen production is affected by the efficiency issue: only one fourth of the energy used to produce hydrogen is available to use from hydrogen's chemical form. The efficiency of water electrolysis process can be improved by using high temperature electrolysis.

Small modular nuclear reactors, especially high temperature gas cooled reactors, can provide high temperature steam and electricity for hydrogen production. Compared to traditional nuclear power plants, SMRs are smaller in size, and their effective electrical power is lower. The safety systems of SMRs are inherent and passive which makes them safer to operate and introduces the possibility of locating the power plants near industrial buildings. However, SMRs are still in their development phase which decreases the reliability since practicality is lacking. Even regarding these risks, the low levels of CO_2 emissions released from nuclear power production supports the development of nuclear hydrogen production. Compared to fossil fuel power plants, the carbon footprint is significantly lower throughout the life cycle of a nuclear power plant. Cogeneration of high temperature steam with HTGRs for industrial needs is one possibility for SMR utilization.

The transformation towards decarbonization does not only affect the energy industry. Emission regulations increase the costs of every industrial process that emits greenhouse gases. A national example is the steel industry that is a single source for a significant proportion of Finland's total GHG emissions. Hydrogen direct reduction is a process that has been introduced as an alternative for traditional blast furnace steel production. In HDR, hydrogen is used instead of coke to reduce steel. The development of HDR has offered promising results and steel manufacturing companies consider it the best technology for steel production in the future. The use of VRES in hydrogen production for steel manufacturing forms a demand for a hydrogen storage. SMRs cogeneration possibilities enable the production of electricity and high temperature steam when hydrogen is required consequently decreasing the need for storage. SMR designs are being developed which opens possibilities for the industrial use. Even though no complete process designs exist for NHP in steel manufacturing, it is an example of how diverse the possibilities for hydrogen applications are. The development of both hydrogen economy and small modular nuclear reactors are in progress and possibilities remain undiscovered.

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