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**Political and technological factors shaping the  
future of green hydrogen**

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**ABSTRACT:**

In achieving climate goals, green hydrogen has emerged in several national strategies as a potential alternative. It is intended to reduce carbon dioxide emissions, develop greener industry and strengthen energy security. However, the adoption of green hydrogen still faces significant challenges, such as high production costs and a lack of infrastructure. To overcome these challenges, strong and consistent political support and fast technological development are needed.

This study has been commissioned by ABB Smart Power and aims to understand how political and technological factors influence the deployment of green hydrogen and its potential role in the future energy infrastructure. The aim of the work is also to understand which political factors drive the deployment of green hydrogen in different regions and, in addition, to understand which technical challenges may limit its large-scale deployment and competitiveness with fossil fuels and grey hydrogen. This study aims to provide a company manufacturing low-voltage products with a comprehensive analysis of green hydrogen production technologies and their current challenges, as well as a review of green hydrogen related policies and regulations in Europe, the United States and China. The study creates four different scenarios using the Futures Table method. The scenarios aim to understand the role of green hydrogen in the future energy sector and in particular the technological challenges related to its production and which political decisions will accelerate its deployment. Scenarios help to understand the possible future visions of green hydrogen, which can help organizations make decisions and modify their operating strategies to better adapt to the changing challenges and demands of the operating environment.

Based on the results of the study, strengthening the role of green hydrogen in the energy system requires both fast technological development and strong political support. These two factors interact with each other and reinforce each other's impact. Although green hydrogen is seen as a key means of achieving carbon neutrality and the number of national hydrogen strategies has increased significantly, its wider use in different sectors depends essentially on the strength of political support and the speed of technological development and their combined effect. If political support is weak, the development of green hydrogen may be limited to areas where the private sector is willing to invest. On the other hand, if technological development is slow, the widespread use of green hydrogen will be postponed to the coming decades. In the worst case, if both political support and technological development remain modest, there is a risk that green hydrogen will remain only a short-term phenomenon without a significant role in the energy transition.

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**KEYWORDS:** Green hydrogen, electrolysis, renewable energy sources, climate strategies, scenarios

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**VAASAN YLIOPISTO**
**Tekniikan akateeminen yksikkö**

<b>Tekijä:</b>	Laura Kohtala		
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**TIIVISTELMÄ:**

Ilmastotavoitteiden saavuttamisessa vihreä vety on noussut useissa kansallisissa ilmastostrategioissa esiin. Sen avulla halutaan vähentää hiilidioksidipäästöjä, kehittää vihreämpää teollisuutta ja vahvistaa energiavarmuutta. Vihreän vedyn laajempi käyttöönotto kohtaa kuitenkin vielä merkittäviä haasteita, kuten sen kalliit tuotanto kustannukset ja infrastruktuurin puute. Jotta nämä haasteet saataisiin selätettyä, tarvitaan vahvaa ja johdonmukaista poliittista tukea ja teknologian nopeaa kehitystä.

Tämä tutkielma on tehty toimeksiantona ABB Smart Powerille ja sen tavoitteena on ymmärtää miten poliittiset ja teknologiset tekijät vaikuttavat vihreän vedyn käyttöönottoon sekä ymmärtää sen mahdollista roolia tulevaisuuden energiainfrastruktuurissa. Työn tavoitteena on myös ymmärtää, mitkä poliittiset tekijät ohjaavat vihreän vedyn käyttöönottoa eri alueilla sekä mitkä tekniset haasteet voivat rajoittaa sen laajamittaista käyttöönottoa ja kilpailukykyä fossiilisten polttoaineiden ja harmaan vedyn kanssa. Tällä tutkimuksella pyritään antamaan pienjännitetuotteita valmistavalle yritykselle kattava analyysi vihreän vedyn tuotannon teknologioista ja niiden tämänhetkistä mahdollisuuksista ja haasteita. Lisäksi tutkielman avulla pyritään antamaan yleiskatsaus vihreän vedyn politiikoista ja säädöksistä Euroopassa, Yhdysvalloissa ja Kiinassa. Tutkielmassa luodaan neljä erilaista skenaariota hyödyntäen tulevaisuudentaulukkomenetelmää. Skenaarioiden avulla pyritään ymmärtämään vihreän vedyn mahdollista roolia tulevaisuuden energiasektorilla sekä mitä tuotantoon liittyviä teknologisia haasteita se tulee kohtaamaan ja lisäksi miten poliittiset päätökset vauhdittavat sen käyttöönottoa. Skenaariot auttavat ymmärtämään vihreän vedyn mahdollisia tulevaisuuden kuvia, joiden avulla organisaatiot voivat tehdä päätöksiä ja muokata toimintastrategioitaan sopeutumaan paremmin toimintaympäristön muuttuviin haasteisiin ja vaatimuksiin.

Tutkimuksen perusteella vihreän vedyn roolin vahvistaminen energijärjestelmässä edellyttää sekä nopeaa teknologian kehitystä että vahvaa poliittista tukea. Nämä kaksi tekijää ovat keskenään vuorovaikutuksessa ja vahvistavat toistensa vaikutusta. Vaikka vihreä vety nähdään keskeisenä keinona hiilineutraalisuuden saavuttamisessa ja kansallisten vetystrategioiden määrä on kasvanut merkittävästi, sen laajempi hyödyntäminen eri sektoreilla riippuu olennaisesti poliittisen tuen vahvuudesta ja teknologisen kehityksen nopeudesta sekä näiden yhteisvaikutuksesta. Mikäli poliittinen tuki on heikkoa, vihreän vedyn kehitys voi rajoittua alueille, joilla yksityinen sektori on valmis investoimaan. Toisaalta, jos teknologian kehitys on hidasta, siirtyy vihreän vedyn laajempi käyttöönotto tuleville vuosikymmenille. Pahimmassa tapauksessa, mikäli sekä poliittinen tuki että teknologinen kehitys jäävät vaatimattomiksi, on vaarana, että vihreä vety jää vain lyhytaikaiseksi ilmiöksi ilman merkittävää roolia energiasuunnitelmassa.

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**AVAINSANAT:** Vihreä vety, elektrolyysi, uusiutuvat energialähteet, ilmastostrategiat, skenaariot

## Contents

1	Introduction	8
1.1	Objectives of the thesis	8
1.2	Research questions	9
1.3	Structure and scope of the thesis	10
2	Electrolyser technologies and their integration with solar and wind power	12
2.1	Green hydrogen	12
2.2	Electrolysers for green hydrogen production	14
2.2.1	Alkaline electrolysers	15
2.2.2	Proton exchange membrane electrolysers	17
2.2.3	Solid oxide electrolysers	18
2.2.4	Anion exchange membrane electrolysers	20
2.2.5	Comparison of electrolyser types in green hydrogen production	21
2.3	Electrolyser co-locating with solar and wind power	24
3	Green hydrogen policies and regulations by region	27
3.1	Green hydrogen policies and regulations in European Union	30
3.1.1	Green hydrogen strategies and targets in the EU	30
3.1.2	EU renewable directive and hydrogen acts	33
3.1.3	EU funding for green hydrogen	35
3.2	Green hydrogen policies and regulations in the United States	37
3.2.1	Green hydrogen strategies and targets in the USA	39
3.2.2	Regulatory challenges and requirements in the USA	40
3.2.3	Subsidies and incentives in the USA	40
3.3	Green hydrogen policies and regulations in China	41
3.3.1	Hydrogen strategies and targets in China	42
3.3.2	Regulatory challenges and requirements in China	43
3.3.3	Subsidies and incentives in China	43
3.4	Comparison of green hydrogen policies and regulations	44
4	Research methodology and scenario analysis	47

4.1	Research methodology	47
4.2	Scenario development	48
4.2.1	Topic and objectives of the scenario work	51
4.2.2	Operational environment analysis	52
4.2.3	Table of the future	55
4.2.4	Creating future visions	55
4.3	Scenarios for the future of green hydrogen	58
4.3.1	The era of green hydrogen	59
4.3.2	Green hydrogen economy without innovation	63
4.3.3	Green hydrogen economy without political support as technology leads	65
4.3.4	From vision to lost opportunity in green hydrogen development	67
4.3.5	Summary of scenarios	69
5	Discussion and Conclusions	72
6	Summary	78
	References	81

## Figures

<b>Figure 1.</b> Operating principle of an alkaline electrolyser (IRENA, 2020a).	16
<b>Figure 2.</b> Operating principle of a PEM electrolyser (IRENA, 2020a).	17
<b>Figure 3.</b> Operating principle of a solid oxide electrolyser (IRENA, 2020a).	19
<b>Figure 4.</b> Operating principle of an AEM electrolyser (IRENA, 2020a).	20
<b>Figure 5.</b> Timeline of published hydrogen strategies and roadmaps as of May 2024 (IRENA, 2024).	28
<b>Figure 6.</b> Drivers mentioned in the report published by IRENA (2024) in national green hydrogen strategies published in recent years. VRE: Variable Renewable Energy.	29
<b>Figure 7.</b> The six steps of scenario building. Adapted from Lätti et al. (2022).	48
<b>Figure 8.</b> Future visions for 2030 presented in a four-field framework.	58

## Tables

<b>Table 1.</b> Parameters of different types of electrolysers, adapting (Akyüz, 2024; IRENA, 2023).	23
<b>Table 2.</b> A comparative overview of policies and regulations in the EU, the US and China.	46
<b>Table 3.</b> Review of the operational environment in terms of politics and technology.	54
<b>Table 4.</b> Four-field table of the future.	55

## Abbreviations

AC	Alternating Current
AE	Alkaline Electrolyser
AEM	Anion Exchange Membrane Electrolyser
DC	Direct Current
DOE	U.S. Department of Energy
EMDE	Emerging Markets and Developing Economies
GH	Green Hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kt	Kiloton
LV	Low Voltage
MPPT	Maximum Power Point Tracking
MW	Megawatt
OH	Hydroxide Ions
PEM	Proton Exchange Membrane Electrolyser
RFNBO	Renewable Fuel of Non-Biological Origin
RMB	Chinese Renminbi
SOE	Solid Oxide Electrolyser
VRE	Variable Renewable Energy

## Declaration of AI use

During the preparation of this master's thesis, Laura Kohtala, the author of the thesis used artificial intelligence (ChatGPT-4o) tool in order to develop the language of the thesis and brainstorming. After using ChatGPT, the author reviewed and edited the content and takes full responsibility for the content of the master's thesis.

# 1 Introduction

In recent years, green hydrogen has emerged as a promising alternative clean energy carrier, and its importance in energy planning has grown for many reasons (Hassan et al., 2024; IRENA, 2021). It can help lower carbon dioxide (CO<sub>2</sub>) emissions in hard-to-decarbonize sectors like steel, chemicals, long-distance transport, shipping, and aviation (IRENA, 2021). To establish green hydrogen as part of a sustainable energy system, continuous technological development is needed, as well as consistent political guidance (IRENA, 2021).

Green hydrogen can also improve energy security and enable energy storage and long-distance transportation, making it a sustainable alternative to fossil fuels (Hassan et al., 2024). However, the biggest challenges in the deployment of green hydrogen are high production costs and lack of infrastructure (Hassan et al., 2024). As investments increase and the price of renewable energy used in the electrolysis process decreases, the production costs of green hydrogen are also expected to decrease (Hassan et al., 2024). In turn, the development of a hydrogen economy requires comprehensive investments in production, storage and distribution systems, which is why its promotion must be a priority for policymakers, investors and society (Hassan et al. 2024).

Green hydrogen is seen as having the potential to revolutionize the energy sector and has attracted the attention of progressive industrial companies (IRENA, 2024). These companies have recognized the need to reduce their carbon footprint and want to maintain their competitive advantage in a rapidly changing market and therefore want to be at the forefront of the deployment of green hydrogen (IRENA, 2024).

## 1.1 Objectives of the thesis

The objective of this thesis is to identify and describe the key drivers of change in the development of green hydrogen production and its potential role in the future energy infrastructure. The thesis aims to understand which policy factors are guiding the

production and deployment of green hydrogen in different regions, such as Europe, China and the United States. Understanding national green hydrogen strategies, targets, regulations and investments is essential as they define the regulatory framework, economic incentives and market conditions that influence the large-scale production and integration of green hydrogen into the energy sector. In addition, these factors drive technological development, infrastructure expansion and international cooperation, all of which are important for green hydrogen's competitiveness. It also aims to investigate what conditions are needed for green hydrogen to become competitive with fossil fuels and grey hydrogen. It also aims to understand which technical challenges may limit the large-scale deployment of green hydrogen, as well as the role of legislation and innovation in reducing costs and developing efficiency.

The motivation for this thesis is the urgency of mitigating climate change and to advance energy transition, and the understanding of the future role of green hydrogen. In addition, the research aims to provide a company manufacturing low-voltage products with a comprehensive analysis of the current political and technological situation and challenges of green hydrogen production, as well as the prerequisites for large-scale deployment. This will help the company to strategically prepare for future changes and identify opportunities where its products can play a significant role in the hydrogen production and distribution infrastructure.

## **1.2 Research questions**

To meet the objectives of this thesis, it aims to answer the following research questions:

1. What are the key characteristics, benefits, and challenges of green hydrogen production and electrolysis technologies?
2. How do EU, China and USA support the development of green hydrogen economy?
3. How do political and technological factors depend on each other in green hydrogen production and deployment?

### 1.3 Structure and scope of the thesis

The research consists of six main chapters. The first main chapter is the introduction, which contains the objects, the research questions and the structure and scope of the thesis. This is followed by a chapter that defines the main terms relevant to the thesis: green hydrogen, electrolysers for green hydrogen production, more specifically alkaline, proton exchange membrane, solid oxide and anion exchange membrane electrolysers. This chapter also discusses co-location of electrolysers with wind and solar power and DC power supply for green hydrogen production by electrolysis. The third main chapter gives an overview of the policies and regulations related to green hydrogen in Europe, the United States and China. The fourth main chapter of the thesis creates four different scenarios for the future of green hydrogen, especially from the perspective of technological development and political support. The fifth main chapter is discussion and conclusions, where the results of the study are compiled, and the most important findings presented. Additionally, this chapter also answers the research questions set at the beginning of the thesis. The sixth and final chapter summarizes the study's key findings, presents conclusions, and possible recommendations for future research.

In this thesis, the topic is limited to green or renewable hydrogen, which is produced with renewable energy using electrolysis. However, it is important to understand that the production of hydrogen uses different processes, which affects its environmental impact (Incer-Valverde et al., 2023). Different manufacturing processes have been assigned colours, such as green, grey and blue, which are the most commonly reported colors (Incer-Valverde et al., 2023). According to De Blasio (2024), grey hydrogen refers to hydrogen produced from fossil fuels and blue hydrogen refers to hydrogen produced from natural gas combined with carbon capture and storage. This colour coding helps to understand the climate impacts of hydrogen production and how it supports the transition towards a more sustainable energy economy (De Blasio, 2024). However, there are still no common nomenclature definitions for hydrogen colour classifications, recalls Incer-Valverde et al. (2023).

The study is limited to technological and political aspects, as these are the most significant issues affecting the future of green hydrogen. This limitation simplifies the topic somewhat, as if economic, social and environmental impacts were included, the study would expand and become considerably more complex. Additionally, the study examines political aspects only in the EU, China, and the USA, as these are currently the leading and most significant countries in green hydrogen production.

## **2 Electrolyser technologies and their integration with solar and wind power**

This chapter defines the key concepts for the study. Firstly, the definition of green or renewable hydrogen is discussed, followed by an introduction to the electrolysis technologies used in green hydrogen production, such as alkaline electrolysers, proton exchange membrane electrolysers, solid oxide electrolysers and anion exchange membrane electrolysers and finally a comparison between these electrolysers. This will be followed by a discussion on the co-locating of electrolysers alongside solar and wind power and introduce one of the most important components in this system.

### **2.1 Green hydrogen**

According to Hassan and others (2024) green hydrogen produced via the electrolysis of water powered by renewable energy sources, represents a sustainable and promising alternative for reducing fossil fuels. Production of green hydrogen is based on electrolysis, where water ( $H_2O$ ) decomposes to hydrogen ( $H_2$ ) and oxygen ( $O_2$ ) with electricity (Hassan et al., 2024). When the electricity used in the process comes from renewable sources, such as solar or wind power, the resulting hydrogen is called green or renewable hydrogen (Hassan et al., 2024). This sets it apart from traditional hydrogen production, which depends on fossil fuels like natural gas (Hassan et al., 2024). The applications of green hydrogen are extensive, reaching from transportation and energy production to industry such as steel and cement production, also as feedstock for industrial processes, or for energy storage and grid balancing (Hassan et al., 2024; Ikurowo et al., 2024). With the help of fuel cells, green hydrogen can be produced as emission-free fuel for vehicles or converted back into electricity, without harmful emissions (Hassan et al., 2024). As a renewable and clean fuel, green hydrogen offers a more stable energy source than fossil fuels, whose availability and price can vary (Hassan et al., 2024). Wider utilization of green hydrogen could reduce dependency on imported fossil fuels, strengthen energy independence and increase energy security (Hassan et al., 2024).

Green hydrogen is an important part of the transition towards sustainable energy production, and it is expected to significantly accelerate industrial renewal (Hou & Yang, 2024, p.19). A total of 46 national strategies on hydrogen have been published by May 2024 (IRENA, 2024). As Hou and Yang (2024, p.19) outlined, national hydrogen strategies focus on reducing the cost and improving the efficiency of green hydrogen production, alongside building infrastructure, integrating with renewable energy, developing recovery technologies, ensuring safety and public acceptance, and fostering international collaboration on hydrogen policies and standards.

According to the IEA's 2024 annual report, hydrogen produced via electrolysis was less than 100 kt in 2023 worldwide production, representing only a small fraction of the total hydrogen production (IEA, 2024). Out of the global hydrogen production done through electrolysis, 75% is done in China, Europe and United States (IEA, 2024). The main challenges of green hydrogen are its high costs in electrolysis, transport, the lack of infrastructure for moving and storing it, large energy losses during the process and the lack of strong market systems (IRENA, 2020a). Green hydrogen, produced through electrolysis using renewable energy, remains the most expensive, with costs ranging from 3-7 euros per kilogram, depending on renewable electricity prices and electrolyser efficiency (Morgan, 2025). Grey hydrogen, produced via steam methane reforming without carbon capture, is currently the cheapest, costing approximately 1-2 euros per kilogram, while blue hydrogen, which incorporates carbon capture and storage technologies, is slightly more expensive at around 1.5-3 euros per kilogram (Morgan, 2025). The production costs of green hydrogen are a significant challenge for its large-scale adoption (Ikuerowo et al., 2024). The costs of green hydrogen mostly depend on the used electrolyser technologies and the renewable energy sources used in production (Ikuerowo et al., 2024). However, the price of renewable electricity is falling, so it is important to focus on reducing the cost of electrolysers next (IRENA, 2020a). Strategies for reducing the cost of electrolysers include their design and construction, as larger modules and advanced manufacturing methods can reduce costs (IRENA, 2020a). For example, if the plant size is increased from 1 MW to 20 MW, costs can fall by more than

a third (IRENA, 2020a). Mass production of electrolyzers can also bring significant savings (IRENA, 2020a). One significant factor increasing the price of electrolyzers is the availability of raw materials, as some electrolyser technologies require expensive and rare metals (IRENA, 2020a). Additionally, fluctuations in the electricity supply can reduce the efficiency and flexibility of the system (IRENA, 2020a). Electrolyzers can be tailored to different industrial needs, such as large production plants, remote renewable energy production areas or decentralized small-scale production (IRENA, 2020a). Depending on the intended use, solutions are optimized for either stable hydrogen supply, low logistics costs, or flexible production (IRENA, 2020a).

## **2.2 Electrolyzers for green hydrogen production**

According to Rashidi et al. (2022) electrolyzers can separate water into oxygen and hydrogen by using electricity. Electrolyzers can produce hydrogen of high purity regardless of the electricity source, but when powered by renewable energy, the overall hydrogen production process becomes low carbon, making it suitable for green hydrogen applications such as fuel cells, which also require high purity (Rashidi et al., 2022). Electrolyzers consist of three levels: cell level, stack level and system level (IRENA, 2020a). The cell level is the most important part of the electrolyser, where the electrochemical reaction takes place (IRENA, 2020a). It consists of two electrodes, an anode and a cathode, which are either in a liquid electrolyte or next to a solid electrolyte membrane (IRENA, 2020a). The cell also includes porous layers that help transport substances and remove reaction byproducts, as well as bipolar plates that provide structural support and direct the flow (IRENA, 2020a). The stack level is the wider unit made up of multiple connected cells (IRENA, 2020a). It also includes insulating spacers between electrodes, seals to prevent leaks, frames for structural support, and end plates that help contain fluids and maintain stability (IRENA, 2020a). The system level extends beyond the stack and includes various supporting components, like cooling systems, equipment for hydrogen purification and compression, devices for converting electricity such as transformers and rectifiers, water treatment units and systems for managing gases (IRENA, 2020a). Hydrogen produced by an electrolyser can be transformed back to

electricity by using fuel cells or create a low-carbon fuel blend by mixing natural gas with hydrogen (Rashidi et al., 2022). A low-carbon fuel blend can be used for heat and power generation (Rashidi et al., 2022).

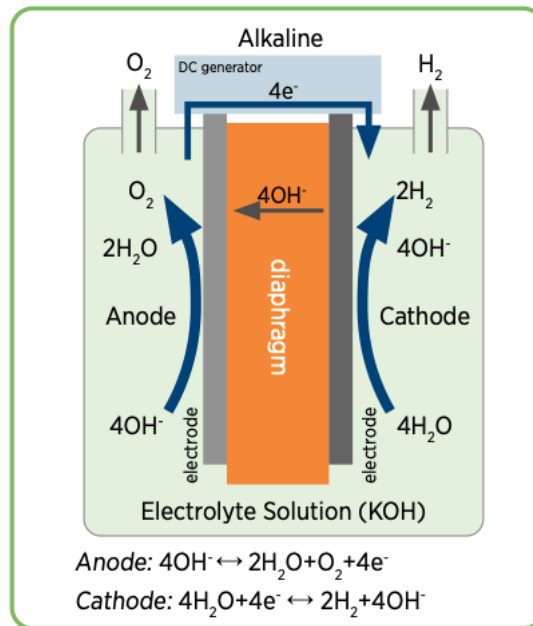
Different types of electrolyzers can be used to produce green hydrogen, which can be divided into four main categories: proton exchange membrane (PEM), alkaline (AE), solid oxide (SOE) and anion exchange membrane electrolyzers (AEM) (Choubey, 2023; Ikuerowo et al., 2024; Guo et al., 2024). According to Ikuerowo et al. (2024), the alkaline electrolyser (AE) is still the dominant technology, but PEM, AEM and SOE electrolysis systems are being developed under pressure. Alkaline (AE) and proton exchange membrane (PEM) electrolysis technologies are mature and widely used in the market, while solid oxide electrolysis (SOE) technology is ready for introduction and commercialization (Ikuerowo et al., 2024). Anion exchange membrane electrolysis (AEM), on the other hand, is still in the development phase and requires further research before large-scale commercial implementation (Ikuerowo et al., 2024). In the industry, the design of an electrolysis plant focuses in particular on hydrogen production rate, energy consumption, current density and production costs (Guo et al., 2024).

The IEA (2024) report states that by the end of 2023, the installed capacity of water electrolyzers worldwide reached 1.4 GW (IEA, 2024). This means that it almost doubled since 2022 (IEA, 2024). However, by September 2024, only 205 MW of new electrolyser capacity had been commissioned, which is much less than predicted (IEA, 2024). Alkaline electrolysis technology continued to dominate in 2023, covering 60% of installed electrolyser capacity (IEA, 2024). In turn, PEM electrolyser technology is gaining more ground, covering 22% of capacity in 2023 (IEA, 2024). China clearly leads in electrolyser manufacturing capacity (IEA, n.d.).

### **2.2.1 Alkaline electrolyzers**

According to Choubey (2023) an alkaline electrolyser (AE) contains water and a liquid electrolyte solution, often potassium hydroxide (KOH) or sodium hydroxide (NaOH).

Hydroxide ions (OH<sup>-</sup>) move through the electrolyte solution from the cathode to the anode when current is supplied to the cell (Choubey, 2023). Hydrogen gas is formed at the cathode and oxygen gas is formed at the anode (Choubey, 2023). Figure 1 shows an illustrative picture of the operating principle of an alkaline electrolyser.



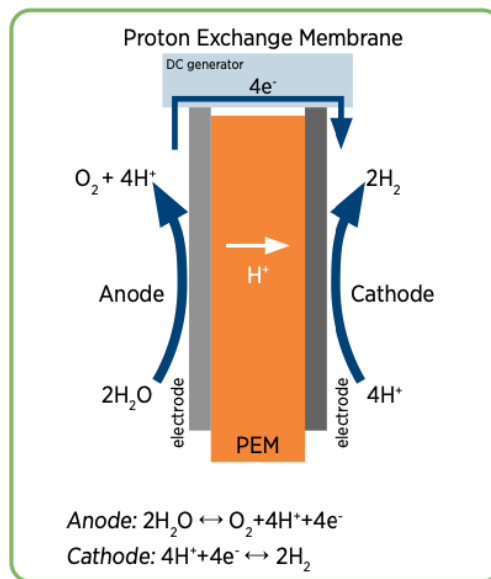
**Figure 1.** Operating principle of an alkaline electrolyser (IRENA, 2020a).

The alkaline electrolyser technology is the first created water electrolysis technology, so it is most mature and widely used (Guo et al., 2024). The construction of alkaline electrolyser systems is significantly cheaper than proton exchange membrane electrolyser systems, only 20-25% of the costs of PEM electrolyser (Hong et al., 2024). The operating temperature of an alkaline electrolyser is 70-90 °C and its efficiency 65-70% (Akyüz et al., 2024; IRENA, 2023). Alkaline electrolyser systems have good durability, long lifetime and mature technology, and these systems are increasingly being used in areas with abundant solar and wind resources to enhance hydrogen production (Dash et al., 2024; Hong et al., 2024). The alkaline electrolyser utilizes inexpensive materials and produces moderately pure hydrogen (Akyüz et al., 2024). In addition, its reactions proceed by providing accessible hydroxyl groups, and a wide range of catalysts are available (Akyüz et al., 2024). However, the challenges are lower current density of 0.2-0.8 A/cm<sup>2</sup> and lower voltage efficiency, slow response time and poor adaptability to

renewable energy due to the intermittent nature of wind and solar power (Hassan et al., 2024; IRENA, 2023). While the technology may require expensive catalysts such as platinum and iridium, its less corrosive conditions also allow the use of cheaper metal catalysts (Akyüz et al., 2024). For this reason, alkaline electrolysis remains a key solution for large-scale hydrogen production (Akyüz et al., 2024). Green hydrogen produced by AE electrolyser is often used in industrial applications, as for example in metal production and as energy storage for excess electricity available from renewable energy sources, which can later be converted back into electricity (Choubey, 2023).

### 2.2.2 Proton exchange membrane electrolyzers

Akyüz et al. (2024) write that the proton exchange membrane electrolyser (PEM) utilizes a solid membrane that acts as an electrolyte. It allows the separation of hydrogen and oxygen simultaneously, continues Akyüz and others (2024). Water is fed into the electrolyser at the anode side and the water is decomposed by the action of an electric current, releasing oxygen at the anode and positively charged protons moving through the polymer membrane to the cathode (Akyüz et al., 2024). At the cathode, the protons combine to form hydrogen gas (Akyüz et al., 2024). Figure 2 shows the operation of a PEM electrolyser.



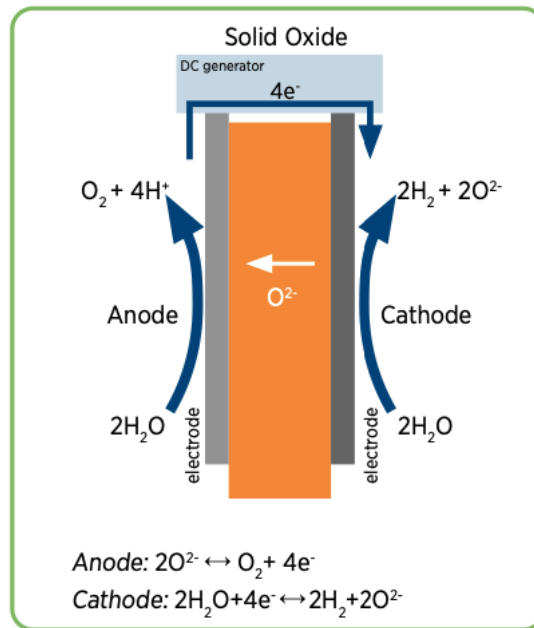
**Figure 2.** Operating principle of a PEM electrolyser (IRENA, 2020a).

The operating temperature of the proton exchange membrane electrolyser is 50-80 °C and the efficiency is 60-70% (Akyüz et al., 2024). Proton exchange membrane electrolysers offer several advantages over other types of electrolysers (Wilberforce et al., 2023). For example, they have lower energy consumption and lower operating temperatures than solid oxide electrolysers, making them particularly suitable for hydrogen production (Wilberforce et al., 2023). PEM electrolysers are excellent for balancing the electrical grid and handling varying loads, as they respond quickly and operate at high current densities of 1-2 A/cm<sup>2</sup> (Akyüz et al., 2024). PEM electrolysers are also compact and lightweight, making them suitable for both local and mobile use (Akyüz et al., 2024). On the other hand, they are more expensive and have lower durability (Wilberforce et al., 2023; Yue et al., 2021). The use of expensive catalysts, such as platinum and iridium, increases costs and limits the choice of anode materials (Akyüz et al., 2024). Also, sensitivity to water impurities can cause challenges (Akyüz et al., 2024).

PEM electrolysers are used in green hydrogen production, portable and small-scale applications, and fuel cell vehicles (Choubey, 2023). Small-scale applications may include backup power systems, off-grid energy solutions and small-scale hydrogen production systems (Choubey, 2023). Proton exchange membrane electrolysers are popular for these applications due to their compact design and fast response time (Choubey, 2023).

### **2.2.3 Solid oxide electrolysers**

Solid oxide electrolyser (SOE) utilize heat to make hydrogen from steam, instead of liquid water (Zhang & Zhang., 2023; Choubey, 2023). There is no need for further separation, when steam will be electrolyzed at the cathode, producing hydrogen here and oxygen is transported by the solid electrolyte to the anode (Zhang, S. & Zhang, N., 2023). Figure 3 presents the operating principle of solid oxide electrolyser.



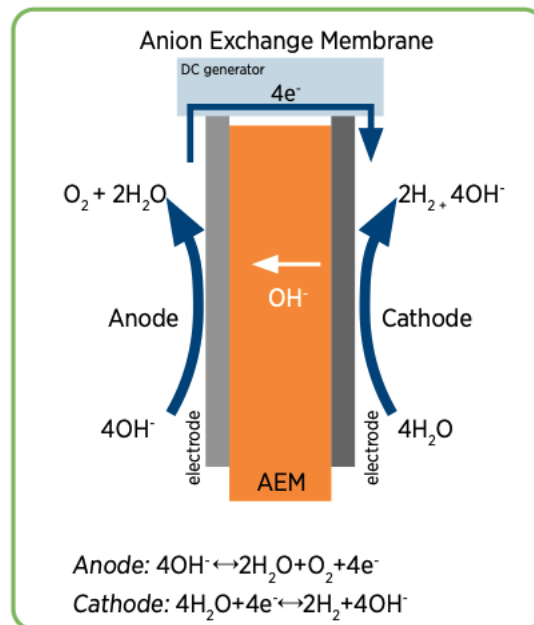
**Figure 3.** Operating principle of a solid oxide electrolyser (IRENA, 2020a).

SOE electrolyzers are often placed where a heat source is available, for example at nuclear or industrial facilities, and they operate at high temperatures of 700-850 °C (Choubey, 2023; IRENA, 2023). Solid oxide electrolyzers have the significant advantage of using thermal energy beside of electrical energy, because heat costs less than electricity (Zhang & Zhang, 2023). Additionally, SOE electrolyzers efficiency can reach up to 90%, with a current density ranging is around 0.3-1 A/cm<sup>2</sup> (Zhang & Zhang, 2023; Akyüz et al., 2024).

Although SOE electrolyzers offer high efficiency, low electricity consumption, and long service life, their high operating temperatures can reduce the durability of materials and make the system more complex, leading to slower response and startup times and higher cost (Akyüz et al., 2024). Additionally, the system needs a large amount of heat energy to vaporize the water, and the oxygen and hydrogen produced in the electrolysis process must be cooled for compression and storage (Zhang & Zhang, 2023). The 1 bar operating pressure of the SOE electrolysis system poses challenges, since the produced hydrogen's low pressure requires additional compression stages and equipment (Zhang & Zhang, 2023).

### 2.2.4 Anion exchange membrane electrolyzers

The anion exchange membrane electrolyser (AEM) system is an emerging technology in green hydrogen production that utilizes cost-effective non-noble metal oxide electrocatalysts (Ikuerowo et al., 2024). These catalysts can produce very pure hydrogen at high pressures (Ikuerowo et al., 2024). AEM separates the formed hydrogen and oxygen gases and at the same time enables the immediate passage of  $\text{OH}^-$  ions and  $\text{H}_2\text{O}$  molecules through the membrane (Vindoh et al., 2023). This helps to balance the electrical charges and supply the substances needed for the reactions to the anode and cathode, where the oxidation and reduction reactions take place (Vindoh et al., 2023). Figure 4 shows the operating principle of anion exchange membrane electrolyser.



**Figure 4.** Operating principle of an AEM electrolyser (IRENA, 2020a).

AEM electrolyzers have operating temperatures of 40-60 °C, current density of 0.2-2  $\text{A}/\text{cm}^2$  and an efficiency of 50-60 % (Akyüz et al., 2024; IRENA, 2023). AEM electrolyzers use non-noble metal catalysts, which are cheaper, making them a more affordable electrolysis option (Akyüz et al., 2024). They are also more pH-tolerant and safer due to their less aggressive alkaline environment (Akyüz et al., 2024). However, the commercial

use of non-noble metal oxide electrocatalysts in AEM systems faces challenges such as the limited activity and durability of the catalysts (Ikuerowo et al., 2024). A critical issue is the slow reaction kinetics due to four-electron transfer, which limits the efficiency of the oxygen evolution reaction (Ikuerowo et al., 2024). Enhancing this process is essential to improve the reactivity and applicability of catalysts (Ikuerowo et al., 2024). The AEM electrolyser has a compact structure and consists of polymer-supported and anion-exchange functional components that improve ion flow and membrane durability (Vindoh et al., 2023).

### **2.2.5 Comparison of electrolyser types in green hydrogen production**

There is no single electrolyser technology that excels in all aspects, instead the future technology mix will be shaped by innovation and competition, driving advancements and improving the suitability of different technologies and system designs for specific applications (IRENA, 2020a). Each type of electrolyser has its strengths and challenges (Akyüz, 2024). Alkaline electrolysers have functional reaction kinetics but adapting them to renewable energy sources is challenging (Akyüz et al., 2024). In turn, the expensive catalysts used in the PEM electrolyser are a challenge, although the electrolyser is more efficient (Akyüz et al., 2024). The SOE electrolyser has a very good efficiency, but its high operating temperature brings its own challenges and the AEM electrolyser combines the benefits of alkaline and PEM technology with the most affordable materials, but it is still in the development stage (Akyüz et al., 2024). Application needs, efficiency requirements and resources determine the choice of electrolyser type, and continuous research promotes their performance and expands the application possibilities (Akyüz et al., 2024). Enhancing an electrolyser stack's performance in one area often reduces other factors like efficiency, cost, lifespan, strength, or manufacturability (IRENA, 2020a). These trade-offs are managed through material and manufacturing innovations, leading to system designs suited for different applications (IRENA, 2020a). Major technological breakthroughs could significantly lower stack costs, while balance-of-plant improvements will mainly come from scaling up production, standardizing designs and supply chains, and learning from experience (IRENA, 2020a). Below is a table (Table 1) of

parameters and their values for different electrolyser types to make it easier to compare them. The table was created by combining information from the research article by Akyüz et al. (2024) and IRENA's (2023) report.

**Table 1.** Parameters of different types of electrolyzers, adapting (Akyüz, 2024; IRENA, 2023).

Parameters:	Alkaline	PEM	Solid oxide	AEM
Operating temperature	70-90 C°	50-80 C°	700-850 C°	40-60 C°
Pressure	1-30 bar	< 70 bar	1 bar	< 35 bar
Nominal electric current density	0.2-0.8 A/cm <sup>2</sup>	1-2 A/cm <sup>2</sup>	0.3-1 A/cm <sup>2</sup>	0.2-2 A/cm <sup>2</sup>
Voltage range	1.4-3 V	1.4-2.5 V	1.0-1.5 V	1.4-2.0 V
Efficiency	65-70 %	60-70%	80-90%	50-60 %
Operational lifetime (stack)	60 000 h	50 000-80 000 h	< 20 000 h	> 5 000 h
Cold start-up time to nominal load	< 50 min	< 20 min	> 600 min	< 20 min
Capital costs (stack) minimum 1 MW	USD 270/kW	USD 400/kW	> USD 2 000/kW	unknown
Capital costs (system) minimum 10 MW	USD 500-1000/kW	USD 700-1 400 USD/kW	unknown	unknown
Scalability	Moderate to high	High	Low to moderate	High
System complexity	Low	High	High	Moderate

### 2.3 Electrolyser co-locating with solar and wind power

According to Tao et al. (2022) electrolyser co-locating with solar and wind power, is an efficient way to produce large amounts of green hydrogen and offers lower power loss and lower system costs than long-distance power transmission. Currently, only AE and PEM electrolysers are used in co-location of solar and wind power, because solid oxide electrolysers operate at such a high temperature and maintaining a high temperature around the clock with solar and wind power is a challenge (Tao et al., 2022). Today, most commercial electrolysers draw electricity as alternating current (AC) from the mains, although cell stacks operate on direct current (DC) (Tao et al., 2022). Therefore, all supporting components of electrolysis systems, such as pumps, are designed to operate on alternating current (Tao et al., 2022).

According to Ikuerowo et al. (2024) green hydrogen can be produced using solar power in three different ways: electrochemical, photoelectrochemical and thermal methods. In the electrochemical method, the solar panels generate electricity for the electrolyser, which produces green hydrogen (Ikuerowo et al., 2024). In this process, the electricity from the solar panels is fed to the electrolyser through a power control unit that includes maximum power point tracking (MPPT) and a DC/DC converter to improve power transmission and control (Ikuerowo et al., 2024). The thermal method uses concentrated solar energy to produce heat, which is directed to an organic rankine cycle (ORC) (Ikuerowo et al., 2024). With the help of high temperatures, the electrolyser can split water into water and oxygen (Ikuerowo et al., 2024). The photochemical method uses solar energy to split water (Ikuerowo et al., 2024). Solar activation begins with the light-sensitive material which creates charge carriers and enables the production of hydrogen through the process (Ikuerowo et al., 2024). The wind power and electrolyser system can be implemented in several different ways, such as a completely grid-independent installation or in such a way that wind energy is used as a power source for the electrolyser when production exceeds consumption (Ikuerowo et al., 2024). In addition, the system can include a storage component and a fuel cell for power generation or be

connected to the power grid (Ikuerowo et al., 2024). A wind-powered electrolysis system for hydrogen production faces different challenges than a solar-powered system (Tao et al., 2022). This is because wind turbine generators produce alternating current (AC) while solar panels produce direct current (DC) (Tao et al., 2022). One way to improve the power factor of the electrolyser is to combine wind and solar energy, as the system offers a continuous production advantage as it depends on two complementary energy sources, which reduces the problems associated with intermittent energy production (Ikuerowo et al., 2024; Tao et al., 2022). Such a hybrid solution can increase the capacity factor of the hydrogen production system by up to 50% (Tao et al., 2022). However, the challenges are how to combine variable AC and variable DC for DC electrolysers, and finding the right sizing between the wind generator, PV system and electrolyser at a given location to maximize capacity factor and keep upfront costs low (Tao et al., 2022). Hybrid systems that produce green hydrogen can be classified into on-grid and off-grid systems (Ikuerowo et al., 2024). On-grid systems are connected to the electricity grid, so they can feed surplus electricity into the grid and, if necessary, take more electricity from the grid to use the electrolyser (Ikuerowo et al., 2024). Off-grid systems, on the other hand, operate completely independently without connection to the electricity grid (Ikuerowo et al., 2024).

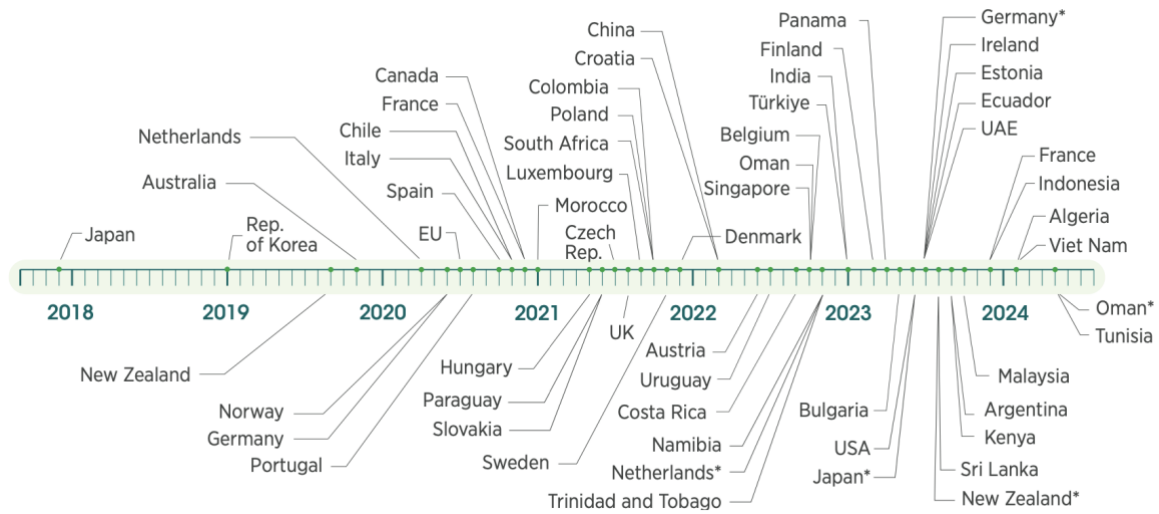
According to Guo and others (2024), in green hydrogen production, renewable energy sources, such as wind and solar energy, generate electricity that is fed into a hydrogen production unit. This unit converts the supply voltage to suit the electrolysis process, after which the electricity is fed into an electrolyser unit that produces hydrogen (Guo et al., 2024). The hydrogen production unit consists of a power supply and an electrolysis unit, where the power supply adapts the voltage of the renewable electricity to the needs of the electrolysis process (Guo et al., 2024). This ensures the stability of the electrolysis process, which is crucial for achieving high hydrogen purity and efficiency (Guo et al., 2024). The power supply constitutes a significant cost factor at the electrolyser system level, approximately 20-30% of the total costs, so there is a great saving potential (IRENA, 2020a).

According to Guo and others (2024), in the power supply system, photovoltaic power is generated by direct current, whereby a DC bus is often used in the hydrogen supply system, which is connected to the electrolysis unit by means of a switch. Depending on the connection method, the solar panel can be connected directly to the electrolysis unit, bypassing the controller and converter (Guo et al., 2024). This direct connection simplifies the design and reduces costs but is not suitable if the panel voltage does not match the requirements of the electrolysis device (Guo et al., 2024). In indirect connection, the solar panel is connected via a controller and a DC/DC converter, which is the more common method (Guo et al., 2024). Wind power generates alternating current, so the hydrogen generation system has an AC bus with an AC/DC converter inserted between it and the electrolysis device to ensure a reliable power supply (Guo et al., 2024). Regardless of whether the hydrogen generation system uses AC or DC bus, the electricity produced is DC with low voltage and high current (Guo et al., 2024). Therefore, a DC/DC or AC/DC converter is an essential part of a power electronics system in hydrogen production (Guo et al., 2024).

### 3 Green hydrogen policies and regulations by region

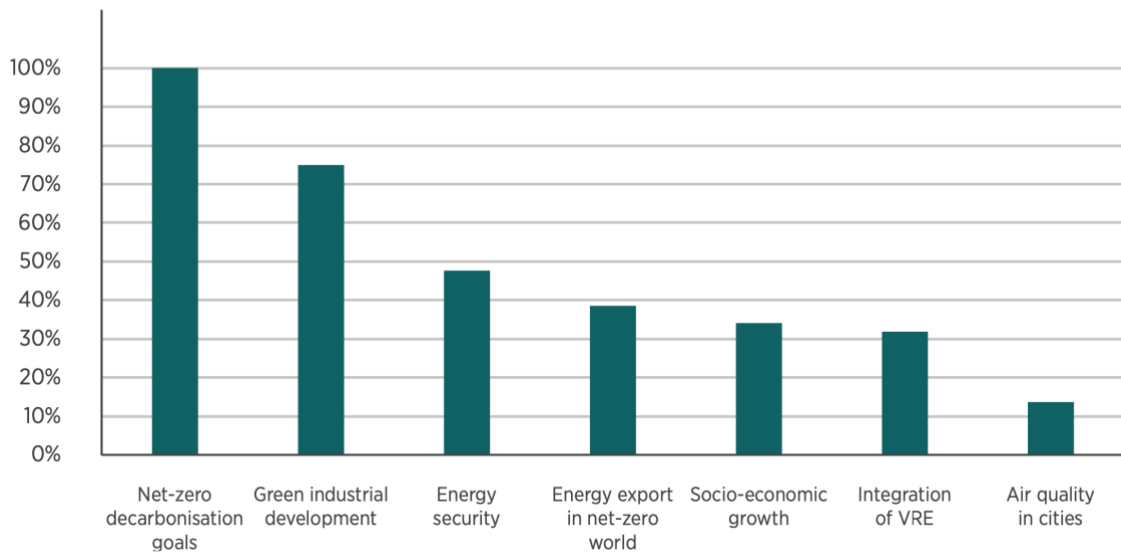
Policies and regulations play a key role in the development of green hydrogen by providing investment certainty, guiding technology development and enabling the construction of infrastructure (Green Hydrogen Organization, n.d.). In addition, regulatory predictability and transparency increase the attractiveness of investment and promote the emergence of hydrogen markets (Green Hydrogen Organization, n.d.).

IRENA (2024) states that 46 hydrogen strategies and 8 roadmaps have been published around the world by May 2024 (Figure 5). In addition, at least 20 countries are preparing their own hydrogen plans and in total at least 74 countries are involved in the strategic development of hydrogen (IRENA, 2024). The strategies emphasize the reduction of carbon dioxide emissions, energy security, industrial development and hydrogen export opportunities (IEA, 2024). During the past year there have been published in total 19 new country-specific strategies with Europe leading the way by having launched 7 strategies, followed by Africa with 4 strategies and ASEAN countries with 3 strategies (IEA, 2024). These new strategies focus mainly on enhancing export and domestic industry, but no strategies have been prepared for the import of hydrogen (IEA, 2024). However, political support is currently shifting from strategic plans into more concrete actions, such as policies and financing programs aimed at reducing the cost gap between low-emission and fossil hydrogen (IEA, 2024). In emerging markets, financial incentives are still limited (IEA, 2024). Even if funding is a fraction of the investment needed to achieve net zero, it will be an important step forward for the emerging hydrogen sector (IEA, 2024).



**Figure 5.** Timeline of published hydrogen strategies and roadmaps as of May 2024 (IRENA, 2024).

Hydrogen strategies published since 2017 show that nations are strongly interested in green hydrogen as a decarbonization solution and an industrial development opportunity, according to an IRENA report (2024). The strategies focus is more on the primary use of hydrogen in sectors where reducing emissions is more difficult (IRENA, 2024). Additionally, strategies prioritize the use of green hydrogen in long-haul trucks, aviation, shipping, and buses, while placing less emphasis on power generation, trains, fuel cell cars, and residential heating (IRENA, 2024). This so-called new wave of interest is based on the Paris Climate Agreement published in 2016 (IRENA, 2024). Below is a bar chart published by IRENA in a report (2024) showing the drivers mentioned in national hydrogen strategies (Figure 6).



**Figure 6.** Drivers mentioned in the report published by IRENA (2024) in national green hydrogen strategies published in recent years. VRE: Variable Renewable Energy.

According to the report, all or more than 70% of the reviewed national strategies published after 2017 include a strong interest in green hydrogen as a decarbonization solution and industrial development opportunity (IRENA, 2024). Fewer strategies prioritize energy security, hydrogen export in a net-zero world, socio-economic growth, integration of Variable Renewable Energy (VRE) and improving air quality in cities (IRENA, 2024). The drivers mentioned in the national hydrogen strategies were assessed using a scoring system, where their priority was classified as high, low or none (IRENA, 2024).

The IEA (2024) report reveals that, public funding on the supply side is almost 1,5 times bigger than on the demand side. This may reflect a shift from imports towards developing domestic green hydrogen production capacity and, in the long term enable its export. In developed markets, public subsidies are the most common incentive, while in emerging markets and developing economies (EMDE) tax incentives are preferred (IEA, 2024). According to the report, nine countries have established incentives to support electrolyser and fuel cell manufacturing, but policies are currently in effect in only six of them (IEA, 2024).

### **3.1 Green hydrogen policies and regulations in European Union**

This chapter first examines the general geopolitical situation of the European Union (EU), followed by a review of its green hydrogen strategy and targets. Additionally, it discusses two EU delegated regulations related to green hydrogen and concludes with an overview of the funding allocated to green hydrogen initiatives.

According to Huttunen (2024), the European Union faces a challenging start to the next five years, despite largely overcoming the 2022 energy crisis. After being elected for a second term in July 2024, European Commission President Ursula von der Leyen built her second commission in a vastly different context compared to her first term as the Commission President (Huttunen, 2024; European Commission, n.d.-a). The 2024 European Parliament elections highlighted a shift from climate-focused priorities to themes of industry and competitiveness, emphasizing a more autonomous and resilient Europe (Huttunen, 2024). Geopolitical uncertainty persists, necessitating significant investments in both military and civilian security sectors (Huttunen, 2024). The political landscape in many member states, including Germany and France, remains unstable and could therefore undermine EU climate policy (Huttunen, 2024; Corbeau, 2024). In France, the growing influence of far-right parties could delay renewable energy expansion and obstruct ambitious Green Deal initiatives in the European Council (Corbeau, 2024).

#### **3.1.1 Green hydrogen strategies and targets in the EU**

The European Union's hydrogen strategy, published four years ago in 2020, aims to reduce carbon dioxide emissions in hard-to-reduce sectors and achieve climate neutrality by 2050 (European Commission, 2020; Fonseca et al., 2024). The European Commission set a target in 2020 to install at least 6 GW of hydrogen electrolyzers in the EU and produce 1 million tons of green hydrogen by 2024, but this target will not be achieved (European Commission, 2020; Fonseca et al., 2024). A second target was set to install at least 40 GW of hydrogen electrolyzers and produce 10 million tons of green hydrogen by 2030 (European Commission, 2020). The EU has also published the

RePowerEU plan in 2022, which aims to produce 10 million tons of green hydrogen for the internal market and import 10 million tons of green hydrogen into the EU by 2030 (European Court of Auditors, 2024). This RePowerEU plan was developed in the wake of Russia's war of aggression against Ukraine, as renewable hydrogen can help reduce fossil fuel imports from Russia (European Court of Auditors, 2024). European Court of Auditors (2024) predicts in its special report, that the targets set for 2030 are also too ambitious and will not be achieved.

The European Union's hydrogen strategy integrates hydrogen into the EU's energy system integration strategy and is in line with the Paris Agreement, with its emphasis on renewable energy and circularity (European Commission, 2020). Implementation of the EU hydrogen strategy includes creating an enabling regulatory framework, fostering innovation, building large-scale infrastructure and connecting stakeholders through the European Clean Hydrogen Alliance (European Commission, 2020). The EU is also seeking international cooperation to diversify supply chains (European Commission, 2020). The EU hydrogen strategy positions Europe as a global leader in clean hydrogen, driving sustainable growth and supporting the clean energy transition (European Commission, 2020).

The hydrogen strategy for achieving a climate-neutral Europe, saw all 20 of its key actions implemented and completed by the first quarter of 2022 (European Commission, n.d.-b). The priorities of these key actions included investments, infrastructure development, increasing demand, international cooperation, and promoting innovation and research (European Commission, n.d.-b). One key initiative is the Clean Hydrogen Alliance, which has assembled a portfolio of over 840 projects (European Commission, n.d.-b; European Commission, n.d.-e). This portfolio covers hydrogen projects collected by the European Clean Hydrogen Alliance between November 2021 and August 2022 (European Commission, n.d.-e). It includes projects at various stages of development, ranging from planning to implementation, with many expected to become operational by the end of 2025 (European Commission, n.d.-e). Additionally, the InvestEU program has enabled 15

member states to allocate 9.3 billion euros to hydrogen-related projects (European Commission, n.d.-b). These actions support the expansion of hydrogen production and usage (European Commission, n.d.-b). The EU promotes hydrogen utilization, particularly in transportation and energy-intensive industries, through the Sustainable and Smart Mobility Strategy and the Renewable Energy Directive (European Commission, n.d.-b). Common standards and certification systems ensure transparency and environmental integrity in hydrogen production (European Commission, n.d.-b). The EU is planning a comprehensive hydrogen network and supports concrete actions such as the launch of 100 MW electrolyser projects through the Horizon 2020 Green Deal call, which led to the financing of three projects in Germany, the Netherlands, and Portugal and the development of a Carbon Contracts for Difference program, included in the proposed revision of the EU Emissions Trading Scheme, to eliminate infrastructure barriers and ensure smooth market operations (European Commission, n.d.-b). On the global stage, the EU is building strong partnerships with southern and eastern neighborhood partners and advancing international hydrogen standards and technologies to facilitate renewable hydrogen exports (European Commission, n.d.-b). Through the Horizon2020 program and the Innovation Fund, the EU supports technological development to green hydrogen (European Commission, n.d.-b). The Clean Hydrogen Partnership focuses on advancing the green hydrogen production, storage, and distribution of renewable hydrogen with a total funding of 2 billion euros together with private members of the partnership (European Commission, n.d.-b).

As previously mentioned, the EU did not achieve the targets set in its hydrogen strategy for 2024. The following section outlines the key reasons behind this shortfall. EU green hydrogen strategy targets set for 2024, such as increasing electrolysis capacity by 6 GW and producing 1 million tons of green hydrogen, were not achieved (Dokso, 2024). The target was missed by a significant margin, with only 0.5 GW of electrolysis capacity now installed in the EU (Dokso, 2024). According to Dokso (2024), the EU's green hydrogen strategy targets for 2030 are also under threat. The growing gap between EU targets and their implementation highlights the need to develop more effective regulatory and

financing solutions for green hydrogen (Dokso, 2024). The EU's strict delegated regulations for green hydrogen also slow down the achievement of targets, such as criteria for electricity procurement for green hydrogen production and the use of required carbon sources in e-fuels (Dokso, 2024; Renewable Carbon News, 2024). These restrictive and complex delegated regulations slow down investments and make them cost more (Renewable Carbon News, 2024). According to a special report by the European Court of Auditors (2024), the EU's green hydrogen targets for 2024 and 2030 were set without sufficient analysis and commitment from Member States, leading to gaps between the targets and national plans. In addition, regulatory delays created uncertainty and slowed down investment, while market underdevelopment and infrastructure deficiencies prevented large-scale growth in production and use (European Court of Auditors, 2024). Fragmentation of funding and investment slowed the progress of projects, and technological challenges, such as increasing the size of electrolyzers and the availability of components, delayed development (European Court of Auditors, 2024).

### **3.1.2 EU renewable directive and hydrogen acts**

The EU Renewable Energy Directive (EU) 2023/2413, also known as REDIII, was updated in October 2023 (European Court of Auditors, 2024; European Commission, 2023/2413). A directive is a legal act addressed to EU member states, which is binding as to the desired outcome, but leaves the member states free to decide how to implement it in national law (European Union, n.d.-a). The updated directive requires EU member states to ensure together that renewable energy accounts for at least 42.5% of the Union's total energy consumption by 2030 (European Commission, 2023/2413, Art. 1). According to the EU directive, renewable hydrogen could be used as a raw material and energy source in industry, chemical processes, and aviation and maritime transport, especially where direct electrification is not technically possible or competitive (European Commission, 2023/2413). In addition, renewable hydrogen could serve as an energy storage solution that balances systems where renewable energy production varies significantly (European Commission, 2023/2413). Through these directive updates, renewable

hydrogen would contribute to the development of a low-carbon energy system and the achievement of the EU's climate goals (European Court of Auditors, 2024).

The Commission also adopted two delegated acts in 2023 related to green hydrogen (European Commission, n.d.-d). Delegated acts, under Article 290 of the Treaty on the Functioning of the European Union, allow the European Commission to amend or supplement non-essential parts of legislation based on powers granted in a basic act (European Union, n.d.-b). These acts help update regulations to keep up with technological and scientific advancements, while the European Parliament and the Council can object or revoke them (European Union, n.d.-b). The first delegated act (EU) 2023/1184 defines the rules for renewable hydrogen production and specifies the complementarity criteria for renewable electricity (European Commission, 2023/1184). The second delegated act (EU) 2023/1185 establishes the methodology for calculating lifecycle greenhouse gas emissions (European Commission, 2023/1185).

The first European Commission delegated act 2023/1184 stipulates that electricity is considered renewable when there is a direct connection between the renewable energy production facility and the electrolyser, meaning no electricity from the grid is used for electrolysis (European Commission, 2023/1184, Art. 3). Additionally, the renewable energy production facility must have commenced operation no more than 36 months before the electrolyser (European Commission, 2023/1184, Art. 3). However, due to the transitional phase, this requirement is flexible for production facilities built before 2028 (European Commission, 2023/1184, Art. 11). Even if electricity from the grid is used for electrolysis, it can be considered renewable if it meets the criteria for complementarity, geographical correlation, and temporal correlation (European Commission, 2023/1184). Hydrogen production must align with renewable electricity generation through on-site electricity production or power purchase agreements (European Commission, 2023/1184, Art. 6). Geographical correlation requires renewable electricity production to be located near the electrolyser, such as within the same bidding zone (European Commission, 2023/1184, Art. 7). Temporal correlation demands alignment between

renewable electricity and hydrogen production: until the end of 2029 on a calendar-month basis, and from 2030 onwards on an hourly basis (European Commission, 2023/1184, Art. 6). Producers must report production and consumption hourly using certified systems (European Commission, 2023/1184, Art. 8). The EU will assess the impact of these rules in 2028 (European Commission, 2023/1184, Art. 10).

The second delegated act created a method for calculating greenhouse gas emission savings achieved over the lifecycle for Renewable Fuels of Non-Biological Origin (RFNBO) including green hydrogen (European Commission, 2023/1185). It accounts for greenhouse gas emissions throughout the entire lifecycle of fuels, including emissions from upstream production, emissions related to electricity drawn from the grid, emissions from refining processes, and emissions from transporting the fuels to the end user (European Commission, 2023/1185).

### **3.1.3 EU funding for green hydrogen**

The EU estimates that the total funding for hydrogen projects in the period 2021–2027 will be around 18.8 billion euros (European Court of Auditors, 2024). The support will be distributed through several programs, the most important of which are the Recovery and Resilience Facility and the Innovation Fund (European Court of Auditors, 2024). The investment needs are significant, but the Commission lacks a comprehensive picture of these needs and the public funding available (European Court of Auditors, 2024). The EU offers to the industry several funding programs with different rules (European Court of Auditors, 2024). This makes it challenging to identify which program is best suited to a given project. The full potential of hydrogen production in the EU is not yet certain (European Court of Auditors, 2024). So far, member states with a high concentration of hard-to-decarbonize industries have made more progress in developing hydrogen projects (European Court of Auditors, 2024). These projects are either already in an advanced stage or undergoing feasibility studies (European Court of Auditors, 2024).

Horizon Europe is also a central EU funding programme to address climate change and develop the EU's competitiveness and growth (European Commission, n.d.-f). The total budget of the Horizon Europe funding programme is approximately 95.5 billion euros for the years 2021-2027 (European Commission, n.d.-f). Horizon Europe funds projects that promote scientific research, support the development of low-carbon industrial applications and breakthrough technologies, and enable the commercialization of innovations, particularly through small and medium-sized enterprises and start-ups (European Commission, n.d.-f). The programme particularly emphasizes climate objectives, with 35% of the funding allocated to climate action (European Commission, n.d.-f). Horizon Europe is structured around three main pillars: Pillar I focuses on excellent science, Pillar II addresses global challenges and strengthens European industrial competitiveness, and Pillar III promotes innovation across Europe (European Commission, n.d.-f). Particularly, Pillars II and III are central to advancing low-carbon industrial applications and breakthrough technologies such as hydrogen (European Commission, n.d.-f). To promote the hydrogen economy, Horizon Europe supports, among other things, the Clean Hydrogen Partnership initiative and hydrogen valleys development projects, which aim to achieve large-scale deployment of renewable hydrogen production and use (European Commission, n.d.-f).

The European Hydrogen Bank is a Commission initiative published in 2022 to promote renewable hydrogen production and market creation and to increase private investment (European Commission, n.d.-c; Spasowska, 2024). The primary objective of the Hydrogen Bank is to increase private investment in hydrogen value chains across the EU and internationally by connecting renewables to European demand and overcoming the challenges of early-stage investment (European Commission, n.d.-c). The hydrogen bank will support the EU's climate goals while increasing investor confidence and creating competition for finance (Spasowska, 2024). The Hydrogen Bank operates on a fixed premium support model, where the premium is awarded in a hydrogen auction to projects with a potential to scale up to 10 production cycles at a time (Spasowska, 2024). According to Spasowska (2024), the impact of the hydrogen bank may be limited if its

budget is not increased and the subsidy period extended from 10 years to 15. Other challenges may include the current price-based criterion for hydrogen, which concentrates subsidies in regions where green hydrogen production is cheapest (Spasowska, 2024).

### **3.2 Green hydrogen policies and regulations in the United States**

Energy policy in the United States is not unified, as it is divided between federal and state governments and consists of separate regulations, policies, and initiatives (Green Hydrogen Organization, n.d.). However, one of the most significant federal responses to climate change is considered to be the Inflation Reduction Act (IRA), signed into law by former U.S. President Joe Biden in 2022 (Zhou et al., 2024). The primary objective of the Inflation Reduction Act is to reduce air pollution and promote the transition to cleaner and more sustainable energy sources (Zhou et al., 2024). The key provisions of the IRA related to energy and climate include promoting renewable energy, carbon capture and storage, supporting nuclear power, encouraging the use of clean fuels, individual incentives, and the development of green vehicles (Zhou et al., 2024). These measures also indirectly support the growth of green hydrogen production by fostering a cleaner energy infrastructure and reducing reliance on fossil fuels. The IRA includes direct incentives for hydrogen through the clean hydrogen production tax credit (section 45V of the U.S. tax code), which aims to make hydrogen produced via electrolysis more cost competitive (Zhou et al., 2024; U.S. Department of Energy, n.d. -c). Additionally, the IRA provides significant funding for renewable energy sources like wind and solar, which are essential for green hydrogen production (Zhou et al., 2024). The IRA also stimulates demand for clean energy by improving the economic feasibility of sustainable energy projects, further driving the adoption of green hydrogen in various sectors (Zhou et al., 2024). These combined efforts create a more favorable market environment for green hydrogen, reinforcing its role in the U.S. clean energy transition (Zhou et al., 2024).

In November 2021, the Congress passed the Bipartisan Infrastructure Law, which plays a key role in promoting green hydrogen in the United States (U.S. Department of Energy,

2024; U.S. Department of Energy, 2023). As part of this law, the Department of Energy allocated 8 billion dollars to develop regional green hydrogen hubs. (U.S. Department of Energy, 2024). The purpose of these hubs is to create networks of hydrogen producers, users, and local infrastructure to accelerate the use of hydrogen as a clean energy source (U.S. Department of Energy, 2024). In addition, these hubs are intended to create the foundation for a national hydrogen distribution network that reduces emissions in power generation, heavy-duty transportation, and industry, and supports an economically viable hydrogen ecosystem (U.S. Department of Energy, 2024). Seven Hydrogen Hubs have received investment from the Department of Energy (DOE) and these are: Pacific Northwest, California, Heartland, Gulf Coast, Midwest, Appalachian and Mid-Atlantic Hydrogen Hubs (U.S. Department of Energy, 2024).

The new U.S. President, Donald Trump, is not known as an advocate for climate policy (Rubin, 2024). Currently, there is uncertainty in the United States regarding Trump's intentions for Biden's climate law, which has caused instability among renewable energy companies and has been reflected in fluctuations in industry stock prices (Patterson, 2024). According to Rubin (2024) a full-scale repeal of the Inflation Reduction Act under a new president is unlikely, as there is strong Democratic support in the House of Representatives and a weak position for Republicans. While production and investment tax credits are likely to remain, certain aspects, such as energy efficiency grants, may be subject to changes (Rubin, 2024). The qualifications for areas such as clean hydrogen and carbon capture may be adjusted to benefit the fossil fuel industry (Rubin, 2024). The core of the law will remain intact, as its tax credits are designed to promote green investments by companies, reduce costs, and create new jobs, making it difficult to repeal (Rubin, 2024). Additionally, while Trump's policies do not reflect the views of the entire country, as many states continue to pursue climate action independently, the increased discretion given to states in climate decision-making may lead to differences in environmental regulations across the country (United States Environmental Protection Agency, 2025; Costa, 2025).

### **3.2.1 Green hydrogen strategies and targets in the USA**

The United States has developed a comprehensive "National Clean Hydrogen Strategy and Roadmap" to integrate green hydrogen production and use into the country's energy infrastructure (U.S. Department of Energy, 2023). The strategy sets a target of producing 10 million metric tons (MMT) of green hydrogen by 2030, 20 MMT by 2040, and 50 MMT by 2050 (U.S. Department of Energy, 2023). The U.S. clean hydrogen production goals for 2022–2036 focus on technology development, cost reduction, and large-scale deployment (U.S. Department of Energy, 2023). By 2023, the goal is to identify at least three potential production methods, test electrolysis devices, and integrate hydrogen production with nuclear power (U.S. Department of Energy, 2023). By 2026, the goal is to implement demonstration projects with renewable energy, nuclear, and carbon capture and storage, achieve 2 dollars per kilogram for hydrogen produced by electrolysis and improve the performance and cost-effectiveness of electrolysis devices (U.S. Department of Energy, 2023). By 2030, the goal of the Hydrogen Shot initiative is to reduce production costs to 1 dollar per kilogram using various production methods while ensuring cost transparency (U.S. Department of Energy, 2023). Achieving these goals requires investments in technology development and infrastructure to make hydrogen a key part of low-carbon energy production (U.S. Department of Energy, 2023). The strategy aims to prioritize green hydrogen in sectors where low-carbon options are limited, such as industrial processes, heavy transport and energy storage (U.S. Department of Energy, 2023). This hydrogen strategy also aims to reduce the costs of hydrogen production and distribution by developing sustainable and reliable production methods, such as electrolysis, thermal hydrogen production with carbon capture (CCS) and advanced hybrid technologies (U.S. Department of Energy, 2023). Cost reduction will be accelerated by leveraging national research institutions, industry and universities, and by rapidly scaling up hydrogen production and deployment (U.S. Department of Energy, 2023). Regional Clean Hydrogen Hubs will also help reduce distribution costs by locating production and use close to each other (U.S. Department of Energy, 2023). This National Clean Hydrogen Strategy and Roadmap will be updated at least every three years, as required by the Bipartisan Infrastructure Act (U.S. Department of Energy, n.d.-b).

### **3.2.2 Regulatory challenges and requirements in the USA**

According to Bade and Tomomewo (2024) the United States lacks a clear, centralized framework for regulating hydrogen. Current guidelines are fragmented and often grouped into broader categories, such as flammable gases, many of which are outdated (Bade & Tomomewo, 2024). Updated standards and additional research are necessary to meet the government's ambitious hydrogen goals (Bade & Tomomewo, 2024). According to Bade & Tomomewo (2024), it should also be remembered that each US state also has its own hydrogen policies. The U.S. National Clean Hydrogen Strategy and Roadmap lists two regulatory actions for green hydrogen production (U.S. Department of Energy, 2023). The first requires the DOE to develop a clean hydrogen production standard also known as CHPS, and the second mandates the reporting of greenhouse gas emissions from applicable facilities, including reports related to hydrogen production and other relevant source categories (U.S. Department of Energy, 2023).

The Clean Hydrogen Production Standard (CHPS) in the United States defines clean hydrogen as being produced with lifecycle emissions of less than 4 kg CO<sub>2</sub>e per kilogram (U.S. Department of Energy, n.d.-a). Currently, the standard covers emissions from production and upstream activities, but it does not yet include those associated with distribution or end use (U.S. Department of Energy, n.d.-a). Plans are in place to expand the standard in the future to incorporate these additional stages, according to the Department of Energy (U.S. Department of Energy, n.d.-a).

### **3.2.3 Subsidies and incentives in the USA**

The Bipartisan Infrastructure Law allocates support to promote the use of green hydrogen (U.S. Department of Energy, 2024). The law allocates 8 billion dollars for hydrogen hubs, 1 billion dollars to support the clean hydrogen electrolysis program to develop electrolysis technologies, and 500 million dollars for the clean hydrogen manufacturing and recycling programs (U.S. Department of Energy, 2024; Bade & Tomomewo, 2024).

The Inflation Reduction Act also includes a tax credit called the Clean Hydrogen Production Tax Credit (45V) (U.S. Department of Energy, 2025). The tax incentive for green hydrogen production is valid for 10 years and can be as high as 3 dollars per kilogram of hydrogen produced (U.S. Department of Energy, 2025). However, green hydrogen producers must meet certain criteria before they are eligible for the tax credit (U.S. Department of the Treasury, 2025). For example, the lifecycle emissions of hydrogen production must be less than 4 kg CO<sub>2</sub>e per kilogram of hydrogen produced, and the lower the emissions of the green hydrogen produced, the higher the tax credit (U.S. Department of the Treasury, 2025). Requirements for hydrogen produced through electrolysis using renewable or nuclear power include that the electricity generation must correspond to hydrogen production, the electricity must come from the same grid area, and new electricity generation or capacity additions must occur within 36 months (U.S. Department of the Treasury, 2025). Annual electricity matching is allowed until 2030, but after that, it will be required on an hourly basis (U.S. Department of the Treasury, 2025).

According to Bade and Tamomewo (2024), hydrogen-based funding and incentives in U.S. states vary by region, focusing on local priorities and goals. For instance, California has nearly 50 laws and incentives aimed at promoting the use of green hydrogen (Bade & Tamomewo, 2024). These include low-carbon fuel standards and funding programs for building hydrogen refueling stations (Bade & Tamomewo, 2024). Meanwhile, Colorado offers a tax credit of 1 dollar per kilogram of hydrogen, and a total of 25 U.S. states have established or planned incentives to encourage hydrogen adoption (Bade & Tamomewo, 2024).

### **3.3 Green hydrogen policies and regulations in China**

China's statements on future climate goals are particularly important both internationally and domestically, as the influence of the United States on global climate negotiations is expected to wane during the upcoming Trump administration, and it is time for China to release a new international climate commitment this year (Patel, 2025).

The latest major change was that China recognized hydrogen as a traditional energy source in China's National Energy Law in May 2024 (Zhang, 2024). Later, by September 2024, China had adopted more than 32 national, and 188 local policies related to hydrogen energy, as well as 24 standardization-related policies (Zhang, 2024). In 2020, China implemented two key policies focusing on promoting green hydrogen in the transportation sector (Pingkuo & Junqing, 2024). The first policy, notice on the Demonstration and Application of Fuel Cell Vehicles, supports hydrogen fuel cell vehicles (HFCVs) and related infrastructure, providing incentives particularly for major urban areas (Pingkuo and Junqing, 2024). The second policy, New Energy Vehicle Industry Development Plan (2021–2035), emphasizes the development of hydrogen storage and distribution technologies as well as the expansion of refueling infrastructure (Pingkuo and Junqing, 2024). Additionally, a national hydrogen plan was published in 2022 “Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021-2035)” and in 2023 “Hydrogen energy industry standard system construction guide” (Pingkuo and Junqing, 2024).

### **3.3.1 Hydrogen strategies and targets in China**

China has implemented a national hydrogen plan called "Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035)," and, in addition, provinces, cities, and municipalities across China have introduced their own hydrogen plans (IEA, 2023; Lou & Corbeau, 2023). Some regional hydrogen development plans have set more ambitious targets than those outlined in China's national hydrogen plan (Lou & Corbeau, 2023). China's national hydrogen plan is divided into three phases, and the goal of the first phase is to bring 50 000 hydrogen fuel cell vehicles on the road and produce 100 000–200 000 tons of green hydrogen by the year 2025 (Allbright Law Offices, 2022; IEA, 2023). Additionally, the goal of the first phase is to create an institutional and policy environment for the development of the hydrogen economy (Allbright Law Offices, 2022). The goal of the second phase is to develop a system of technological innovation, and a hydrogen production and supply chain based on clean energy by 2030 (Allbright Law Offices, 2022). The goal of the final, third phase is to establish a diversified hydrogen

industry system covering applications in transportation, energy storage, and industry by 2035 (Allbright Law Offices, 2022). The target set by the central government seems modest, while city-specific targets are more ambitious (Miller-Wang, 2023). This may be due to China's past overcapacity problems in the solar and battery industries, which led to national investments being ineffective (Miller-Wang, 2023).

### **3.3.2 Regulatory challenges and requirements in China**

According to the IEA report (2024), China published guidelines for reporting greenhouse gas emissions from industrial plants in 2023 and these can be used as guidance for future regulations on green hydrogen. According to the guidelines, off-grid non-fossil electricity is considered to be emission-free, while emissions from non-fossil fuel electricity have been calculated using a national grid emission factor of 570 g CO<sub>2</sub>/kWh from 2022 onwards, and green certificates can no longer be used to offset emissions (IEA, 2024). In addition, as part of the hydrogen strategy in China, there is a focus on developing standards and safety oversight across the entire value chain, including improving hydrogen-related quality and safety standards and standardizing infrastructure and applications (IRENA, 2024).

### **3.3.3 Subsidies and incentives in China**

According to Dellatte (2023), it is difficult to accurately assess the amount of annual public funding allocated to hydrogen projects in China, but the estimated amount is approximately 71.2 billion yuan. A significant portion of the funding will be directed towards new energy sources and fuel cell technologies (Dellatte, 2023). Several projects, such as green hydrogen production, hydrogen refueling stations, hydrogen storage facilities and mixing gaseous hydrogen into gas pipelines, are also receiving funding (Dellatte, 2023). There are also varying funding mechanisms in place at national and local levels to support green hydrogen projects (Dellatte, 2023).

Additionally, to achieve its goals for fuel cell vehicle deployment, China has a pilot program in place, states Miller-Wang (2023). Selected cities in the program will develop and test fuel cell vehicle technology and related infrastructure (Miller-Wang, 2023). Under the program, city clusters can receive funding if they meet certain requirements, such as deploying more than 1000 fuel cell vehicles, a maximum hydrogen fuel price of 35 RMB/kg, and at least 15 operational hydrogen refueling stations (Miller-Wang, 2023). The central government has approved five city clusters, which aim to deploy a total of 33 010 fuel cell vehicles and 322 refueling stations by 2025 (Miller-Wang, 2023).

### **3.4 Comparison of green hydrogen policies and regulations**

The European Union, the United States, and China have all developed green hydrogen strategies, but their approaches differ significantly in terms of scope, ambition, and regulatory structures (Table 2). Strategic targets are not fully comparable, as the target years vary between regions. An exception is the shared 2030 target of the EU and the USA, where both aim to produce 10 million tons of green hydrogen. China's strategy differs in particular in that it focuses not only on the production of green hydrogen but also on its use in transportation. China aims to have 50 000 hydrogen fuel cell vehicles in operation by 2025, highlighting its focus on promoting hydrogen adoption in the transportation sector (Allbright Law Offices, 2022; IEA, 2023).

There are also substantial differences in the regulatory frameworks for green hydrogen. The European Union has taken significant steps in developing its regulatory system, including Delegated Act (EU) 2023/1184, which defines the criteria for renewable hydrogen production, and Delegated Act (EU) 2023/1185, which sets the methodology for calculating lifecycle greenhouse gas emissions. In the United States, regulation remains fragmented, but hydrogen is still governed under broader flammable gas regulations, and differences exist between states (Bade & Tomomewo, 2024). However, at the federal level, the Clean Hydrogen Production Standard (CHPS) and mandatory greenhouse gas emissions reporting represent steps towards a more unified regulatory approach (U.S. Department of Energy, 2023). One significant difference in regulations

between the regions is that currently, there are notable differences between the EU and the USA in the methods used to calculate the lifecycle emissions of green hydrogen. The European Union's delegated act (2023/1185) is based on a comprehensive lifecycle assessment that accounts for emissions across the entire value chain of RFNBOs, such as green hydrogen from production to end use (European Commission, 2023/1185). In contrast, the United States Clean Hydrogen Production Standard (CHPS) defines clean hydrogen as having lifecycle emissions below 4 kg CO<sub>2</sub>e per kilogram of hydrogen, but for now, it only includes emissions from production and upstream activities (U.S. Department of Energy, n.d.-a). However, according to the U.S. Department of Energy (n.d.-a), there are plans to expand the standard in the future to also cover emissions related to distribution and end use. China has introduced a green hydrogen regulatory framework for reporting greenhouse gas emissions from industrial plants and established principles for treating off-grid renewable electricity as emission-free, but comprehensive green hydrogen legislation is still under development (IEA, 2024; IRENA, 2024). The European Union's advanced and harmonized regulatory framework demonstrates its aspiration to assume a leadership position, the United States emphasizing large-scale and long-term expansion of production with targets reaching up to 2050 in a decentralized regulatory environment, and China focusing on integrating hydrogen into the transport sector, it is likely that each region will have its own role in the future global hydrogen economy.

It is practically impossible to compare subsidies, incentives and public funding between different countries, as the funding mechanisms, forms of support and reporting practices differ significantly. For example, in the United States, in addition to funding, there are tax credits, and funding is provided at the federal level and through the states' own programs. In the EU, funding is distributed at the Union level, but the member states also have their own national support systems, which decentralizes the whole. In addition, the EU has several different funding and support programs, such as the Hydrogen Bank and Horizon Europe, which have different rules. In China, too, support can be obtained from two levels, the central government and the local governments and cities.

**Table 2.** A comparative overview of policies and regulations in the EU, the US and China.

Category:	EU	USA	China
Green hydrogen strategy targets	<ul style="list-style-type: none"> <li>- Install 6 GW of electrolyzers and produce 1 million tons of green hydrogen by 2024.</li> <li>- Install 40 GW of electrolyzers and produce 10 million tons of green hydrogen by 2030.</li> </ul> (European Commission, 2020)	<ul style="list-style-type: none"> <li>- Produce 10 MMT of green hydrogen by 2030.</li> <li>- Produce 20 MMT by 2040.</li> <li>- Produce 50 MMT by 2050</li> <li>- 1 dollar per kg clean hydrogen within a decade</li> </ul> (U.S. DOE, 2023)	<ul style="list-style-type: none"> <li>- Bring 50 000 hydrogen fuel cell vehicles onto the road and produce 100 000–200 000 tons of green hydrogen by 2025</li> </ul> (Allbright Law Offices, 2022; IEA, 2023).
Green hydrogen regulations	1 directive and 2 delegated acts: <ul style="list-style-type: none"> <li>- (EU) 2023/1184: Defines rules for renewable hydrogen production.</li> <li>- (EU) 2023/1185: Establishes lifecycle greenhouse gas emissions calculation methodology.</li> </ul>	<ul style="list-style-type: none"> <li>- No centralized hydrogen regulation: fragmented under outdated flammable gas rules (Bade &amp; Tomomewo, 2024).</li> <li>- Clean Hydrogen Production Standard (CHPS) (U.S. DOE, 2023).</li> <li>- Mandatory GHG emissions reporting (U.S. DOE, 2023).</li> </ul>	<ul style="list-style-type: none"> <li>- Guidelines for GHG emissions reporting from industrial plants (IEA, 2024).</li> <li>- Off-grid non-fossil electricity considered emission-free (IEA, 2024).</li> <li>- Focus on developing standards, quality, and safety (IRENA, 2024).</li> </ul>
Green hydrogen subsidies and incentives	<ul style="list-style-type: none"> <li>- 18.8 billion euros in funding allocated for 2021–2027 to support green hydrogen projects (European Court of Auditors, 2024).</li> <li>- Hydrogen Bank (European Commission, n.d.-c).</li> <li>- Horizon Europe (European Commission, n.d.-f).</li> </ul>	<ul style="list-style-type: none"> <li>- Funding provided through the Bipartisan Infrastructure Law (BIL) (U.S. DOE, 2024).</li> <li>- Tax credits (U.S. DOE, 2025).</li> </ul>	<ul style="list-style-type: none"> <li>- Annual public funding for hydrogen projects totals ~71.2 billion yuan (Dellatte, 2023).</li> <li>- Local governments and cities can access funding if certain criteria are met (Miller-Wang, 2023).</li> </ul>

## **4 Research methodology and scenario analysis**

The purpose of this chapter is to first introduce the research method used in the thesis and justify why this method was selected for this work. The chapter constructs four different scenarios using the Futures Table method. According to Lätti et al. (2022, p.319) Futures Table method is based on the morphological analysis of Fritz Zwicky. The scenarios were created using the four-field scenario framework, where the vertical axis was chosen as strong political support - weak political support and the horizontal axis as fast technological development - slow technological development. With help of the constructed scenarios, the aim is to understand future developments, especially in relation to the production of green hydrogen with electrolyzers. Understanding the potential future of green hydrogen production can help organizations make decisions and modify their operating strategies to better adapt to the changing challenges and demands of their operating environment.

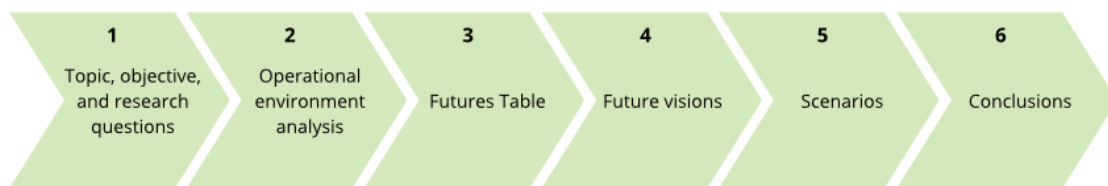
### **4.1 Research methodology**

This study aims to provide future-oriented information that supports current decision-making and action. Its goal is to understand future developments and the interdependencies between them (Lätti et al., 2022, p. 314). One of the most important tools in futures research is scenarios, which can be used to understand different possible paths of change (Lätti et al., 2022, p. 314). A scenario refers to a documented description of possible futures based on collected research data (Lätti et al., 2022, p. 315). It describes cause-and-effect relationships and chains of events that can lead to a specific future situation (Lätti et al., 2022, p. 315). Scenarios play a crucial role in decision-making because they help to gather essential information, identify uncertainties and distinguish between what is possible, impossible, temporary or permanent (Lätti et al., 2022, p. 316). Scenario planning can help us make more informed decisions today by understanding their potential future impacts (Lätti et al., 2022, p. 316). Scenario work focuses on predicting future events and trends, but its real value is in guiding today's actions and decision-making (Lätti et al., 2022, p. 316). It helps us navigate uncertainty with greater

confidence and make choices that are more informed and strategic (Lätti et al., 2022, p. 316). Scenario planning helps to find new opportunities and choose the most sustainable solutions and support the evaluation of previous decisions and strategies in changing circumstances (Rubin, 2004).

## 4.2 Scenario development

In this thesis, scenarios are constructed using the Futures Table method, following the six-step approach outlined by Lätti et al. (2022, p. 319) (Figure 7). In the first step, a topic for the scenario work is selected, objectives and research questions are defined, and the type of category, time span, geographical area and perspective of the scenarios are also defined (Lätti et al., 2022, p. 319).



**Figure 7.** The six steps of scenario building. Adapted from Lätti et al. (2022).

The second step defines the scenario's operating environment, which is used to outline the phenomena related to the scenario topic and its development trends (Lätti et al., 2022, p. 321). This analysis forms a comprehensive overall picture of the topic under review, which includes an examination of key megatrends, trends, uncertainties, weak signals and surprising events (Lätti et al., 2022, p. 321). In this study, scientific publications, statistics, articles and official documents have been used to collect information on the operating environment. In this step, the entire operating environment is defined, which includes political, economic, social, technological and environmental structures that affect the object under study (Lätti et al., 2022, p. 322). Political factors include, for example, legislation and regulation, while economic factors include economic growth, purchasing power and inflation (Lätti et al., 2022, p. 322). Social factors deal with changes in demographic structure and consumption habits, while

technological factors are related to innovations and technological development (Lätti et al., 2022, p. 322). Environmental factors cover both the natural and built environment (Lätti et al., 2022, p. 322). This allows the factors affecting the topic under study to be organized more clearly and ensures that the review is broad-based (Lätti et al., 2022, p. 322). In addition, classified information can be analyzed from the perspective of megatrends, trends, uncertainties, weak signals and surprising events (Lätti et al., 2022, p. 322). Lätti et al. (2022, p. 323) define that megatrends are global, long-term trends that have significant societal impacts. Trends in turn, refer to observable, often gradual changes, the direction of which can be assessed, for example based on historical data (Lätti et al. 2022, p. 323). They are typically shorter-term than megatrends and may be related to, for example, technological development or increased support policies (Lätti et al. 2022, p. 323). Uncertainties describe phenomena whose development direction is unclear or contradictory (Lätti et al., 2022, p. 323). They can consist of opposing forces of change and distinguishing them from trends can be challenging (Lätti et al., 2022, p. 323). In scenario work, assumptions are often made about which uncertainty factors will turn into predictable trends (Lätti et. al., 2022, p. 323). Weak signals are early indications of new phenomena or trends that may grow in importance over time (Lätti et al., 2022, p. 323). They may be related to, for example, technological innovations or societal changes, but are still developing and not widely recognized (Lätti et al., 2022, p. 323). Wild cards are unexpected, infrequent but significant changes, and their prediction is challenging, as they may not have a previous historical background (Lätti et al., 2022, p. 323). Examples of wild cards include pandemics, political upheavals and extreme weather events (Lätti et al., 2022, p. 323).

In the third step, a futures table is created, which helps to outline possible future developments (Lätti et. al, 2022, p. 324). The table brings together the key observations of the operating environment and creates alternative development directions for them (Lätti et. al, 2022, p. 324).

In the fourth step, future visions are created (Lätti et al., 2022, p. 326). Future visions are created based on a futures table, and they act as "freeze frames" of a certain future moment (Lätti et al., 2022, p. 326). The visions depict the end point of the development of the chosen topic over a certain time span (Lätti et al., 2022, p. 326). The future visions are built on an understanding of the present and the past, and it is considering various information, observations, beliefs, expectations, values and emotions, such as hopes and fears (Lätti et al., 2022, p. 326). Future visions are built in two stages: selecting development alternatives and writing out future visions (Lätti et al., 2022, p. 326). In the first stage, alternative development paths are selected for uncertainty factors and different future visions are formed by combining these (Lätti et al., 2022, p. 326). The aim is to make the future visions as different as possible (Lätti et al., 2022, p. 326). In the second stage, the future visions are written out, where the selected development options are combined into a logical and fluent story (Lätti et al., 2022, p. 327). In this thesis the future visions are based on the knowledge and creative thinking discussed in the theoretical chapters two and three of the study, to get an overall picture of possible future development processes. At this step, it is not yet justified how the future has been arrived at, as it is discussed in the next step, where the scenarios are created.

In the fifth step, the future visions created in the previous step are combined with the present time, specifically the year 2025, when this study was conducted. This step involves constructing a narrative for each scenario, beginning from the current situation in 2025 and extending towards 2030. The aim is to illustrate a logical and plausible development path from today's circumstances to the envisioned future states (Lätti et al., 2022, p. 328). Each narrative describes how political, technological factors could evolve over time, helping to provide a coherent storyline that connects the present to the alternative futures outlined in the scenarios.

The final, or sixth step includes conclusions, and a summary of the scenarios created (Lätti et al., 2022, p. 331). In this step, the main findings of the scenario work are gathered and the key insights from the different future paths are presented (Lätti et al.,

2022, p. 332). In addition, this step determines whether the objectives set for the scenarios have been achieved and whether the questions set for the scenario work can be answered (Lätti et al., 2022, p. 331).

#### **4.2.1 Topic and objectives of the scenario work**

This chapter forms the first step in the scenario development process. It defines the topic and objectives of the scenarios, focusing on green hydrogen production, particularly the policies and regulations influencing it, and the development of the electrolyser technologies used. This study uses an exploratory scenario type, which focuses on outlining changes in the operating environment and supporting strategic decision-making. The aim of the scenarios is not to predict the future, but to identify key uncertainties and possible development directions (Lätti et al., p. 362). The geographical focus of the scenarios is Europe, China and USA, and the time span is 2025-2030. The scenarios aim to understand the key change factors in green hydrogen production and what role it can play in the future energy infrastructure. The scenarios support the analysis by offering different possible future paths. Three key objectives have been defined for this scenario analysis, which are accompanied by clarifying questions. These objectives and questions are presented below.

**Objective 1:** To identify the key uncertainties affecting the future of green hydrogen.

- What are the most significant political and technological uncertainties that are affecting the future of green hydrogen?

**Objective 2:** To understand how the key political and technological uncertainties shape the different possible futures for green hydrogen and how they are interdependent.

- How do political and technological uncertainties influence the possible futures of green hydrogen?
- How are political and technological uncertainties interdependent?

**Objective 3:** To understand the potential role of green hydrogen in different future scenarios.

- In which sectors is green hydrogen expected to become the most important energy source by 2030?
- What types of support and innovations are needed for green hydrogen to reach its full potential in the energy sector?
- How could green hydrogen achieve competitiveness with grey hydrogen?

#### **4.2.2 Operational environment analysis**

This chapter represents the second step in the scenario development process. It focuses on the analysis of the operating environment, aiming to examine the phenomena related to the scenario topic and to identify changes affecting them. This thesis focuses on the political and technological factors of the operating environment, as they constitute the key drivers for the development of green hydrogen production and electrolyser technology. To establish green hydrogen as a part of a sustainable energy system, it requires continuous innovation and consistent political decisions (IRENA, 2021). Although economic, social and environmental factors are also significant, examining them would require a broader approach. This limitation allows for a more in-depth examination without the research becoming too complex and fragmented. The theoretical part of this thesis discusses the current state of green hydrogen production technologies and green hydrogen policy, which provides the necessary background information for creating scenarios.

Relevant megatrends for green hydrogen include technological development, emission reduction, the pursuit of energy independence, and international agreements such as the Paris Climate Agreement. In the context of green hydrogen, trends include improvements in electrolyser efficiency, the increasing integration of electrolysers with solar and wind power, the growing number of national green hydrogen strategies and roadmaps, and the overall expansion of green hydrogen related policies. In addition, the decrease in the price of renewable electricity has been a trend for the past decade

(IRENA, 2020b). Political uncertainties relate to the strength of political support for green hydrogen, fragmentation between national green hydrogen policies, the amount of financial support available, the impact of emissions trading systems and carbon taxes, and the development of green hydrogen regulations. Technological uncertainties concern the timing of electrolyser technology development, for example, when solid oxide electrolyser (SOE) and anion exchange membrane (AEM) technologies will enter the market. They also include the timing of green hydrogen infrastructure and storage development, the impact of scalability and mass production, the availability of raw materials, competition with other technologies, and the availability and cost of renewable electricity. Furthermore, technological uncertainties involve the design and structure of electrolysers, their efficiency and flexibility, and the potential applications for green hydrogen. Weak signals pointing to future developments include national support initiatives from developed countries and new electrolyser technologies, such as the hydrogen cooperation between the EU and Morocco and innovations like the Hysata electrolyser (Plank et al., 2023; Hysata, n.d.). Wild cards that could significantly influence the future of green hydrogen include geopolitical conflicts disrupting the development and trade of green hydrogen and renewable energy, and the emergence of new technologies that could replace green hydrogen production. In Table 3 political and technological megatrends, trends, uncertainties, weak signals and wild cards for green hydrogen are defined.

**Table 3.** Review of the operational environment in terms of politics and technology.

	<b>Political</b>	<b>Technological</b>
<b>Megatrends</b>	<ul style="list-style-type: none"> <li>- Reducing emissions</li> <li>- Energy independence</li> <li>- Paris climate agreement</li> </ul>	<ul style="list-style-type: none"> <li>- Technological development</li> </ul>
<b>Trends</b>	<ul style="list-style-type: none"> <li>- National green hydrogen strategies and roadmaps</li> <li>- Increase in green hydrogen support policies</li> </ul>	<ul style="list-style-type: none"> <li>- Development of electrolyser technology, e.g. improving efficiency and integrating wind and solar power</li> <li>- The price of renewable electricity is decreasing</li> </ul>
<b>Uncertainties</b>	<ul style="list-style-type: none"> <li>- Strength of political support to green hydrogen</li> <li>- Fragmentation of national green hydrogen policies</li> <li>- Amount of financial support</li> <li>- The impact of emissions trading and carbon taxes</li> <li>- Development of green hydrogen regulations</li> </ul>	<ul style="list-style-type: none"> <li>- Timing of electrolyser technology development, e.g. when will SOE and AEM enter the market</li> <li>- Timing of green hydrogen infrastructure and storage development</li> <li>- The impact of scalability and mass production</li> <li>- Availability of raw materials</li> <li>- Competition with other technologies</li> <li>- Availability and cost of renewable electricity</li> <li>- Design and structure of electrolysers</li> <li>- Efficiency and flexibility of electrolysers</li> <li>- Utilization of green hydrogen applications</li> </ul>
<b>Weak signals</b>	<ul style="list-style-type: none"> <li>- International collaborations with developing countries regarding green hydrogen (e.g. Cooperation between EU and Morocco)</li> </ul>	<ul style="list-style-type: none"> <li>- New electrolyser technologies (e.g. Hysata)</li> </ul>
<b>Wild cards</b>	<ul style="list-style-type: none"> <li>- Geopolitical conflict disturbing the development and trade of green hydrogen and renewable energy</li> </ul>	<ul style="list-style-type: none"> <li>- New energy technologies are replacing the role of green hydrogen in some applications.</li> </ul>

### 4.2.3 Table of the future

This chapter represents the third step in the scenario development process. It constructs a four-field futures table by combining the key political and technological uncertainties identified in the previous chapter. The table serves as a tool for exploring how different combinations of these uncertainties could shape the future development of green hydrogen. Two main uncertainties were chosen as the basis for the analysis: the strength of political support for green hydrogen and the timing of technological development of electrolysis technologies.

Each of these uncertainties was divided into two opposing development paths. For political support, the options were considered as strong and weak political support. For technological development, two paths were identified: fast and slow technological progress. By combining these dimensions, four distinct futures scenarios can be created, each representing a different combination of political and technological conditions.

**Table 4.** Four-field table of the future.

Uncertainties:	Development direction A:	Development direction B:
Strength of political support to green hydrogen:	Strong political support to green hydrogen	Weak political support to green hydrogen
Timing of electrolyser technology development:	Fast technological development	Slow technological development

### 4.2.4 Creating future visions

This chapter represents the fourth step in the scenario development process. In this section, four different future visions are created based on the futures table (Table 4) constructed in the previous section. The table is used to outline four different future snapshots for the year 2030, and the future visions are formed by combining information about the present and the past, which has been collected earlier in this study, and by combining different own views and expectations. The first future vision is “Strong political support - Fast technological development”, the second future vision is “Strong

political support – Slow technological development”, the third future vision is “Weak political support – Fast technological development” and the last or fourth future vision is “Weak political support – Slow technological development”. At this step, the pathways leading to the future have not yet been justified, as this will be addressed in the next section (chapter 4.3.) where the full scenarios are developed.

**Future vision 1:** (Strong political support – Fast technological development)

Green hydrogen strategies are being implemented in most countries. Green hydrogen production costs have been reduced and are competitive with fossil fuels and grey hydrogen. More electrolyzers have been installed around the world, increasing hydrogen production capacity. Electrolyser technology has advanced and Solid Oxide and AEM electrolyzers have also entered the market. The raw material problems of PEM and alkaline electrolysis devices have been taken up for development, but due to the slow pace of material development, the focus was particularly on system-level innovations, which achieved significant efficiency improvements. Industry, transport and the energy sector have started to implement hydrogen and are expected to utilize further in the coming years. In addition, green hydrogen is also being deployed in developing countries, especially those with the greatest potential for renewable energy. Europe and the US are competing with China for leadership in hydrogen technology, and the global hydrogen market is stable and widespread. Hydrogen production is integrated with renewable energy, and hydrogen storage serves as a balancer in the energy system. Global standards have been set for green hydrogen, and governments have set regulations for its production and use. The hydrogen economy has become one of the key cornerstones of the energy transition.

**Future vision 2:** (Strong political support – Slow technological development)

Green hydrogen has become an integral component in specific industrial sectors. It has been introduced in the steel and chemical industries and in heavy transport, as strong political support has encouraged its introduction in these sectors to meet climate targets. However, the slow development of the technology has hindered the wider adoption of

green hydrogen. Green hydrogen is still expensive and cannot yet fully compete with fossil fuels. Although the price of renewable solar and wind energy has fallen, costs arise from electrolyzers. Alkaline and PEM electrolyzers continue to lead the market, as solid oxide and AEM electrolyzers have not achieved a breakthrough. The market has developed slowly, and the introduction of green hydrogen must be supported by a wide range of mechanisms, such as tax breaks and carbon dioxide tariffs. The largest investments are in industry and limited hydrogen applications. The full breakthrough of the hydrogen economy will move to the next decade.

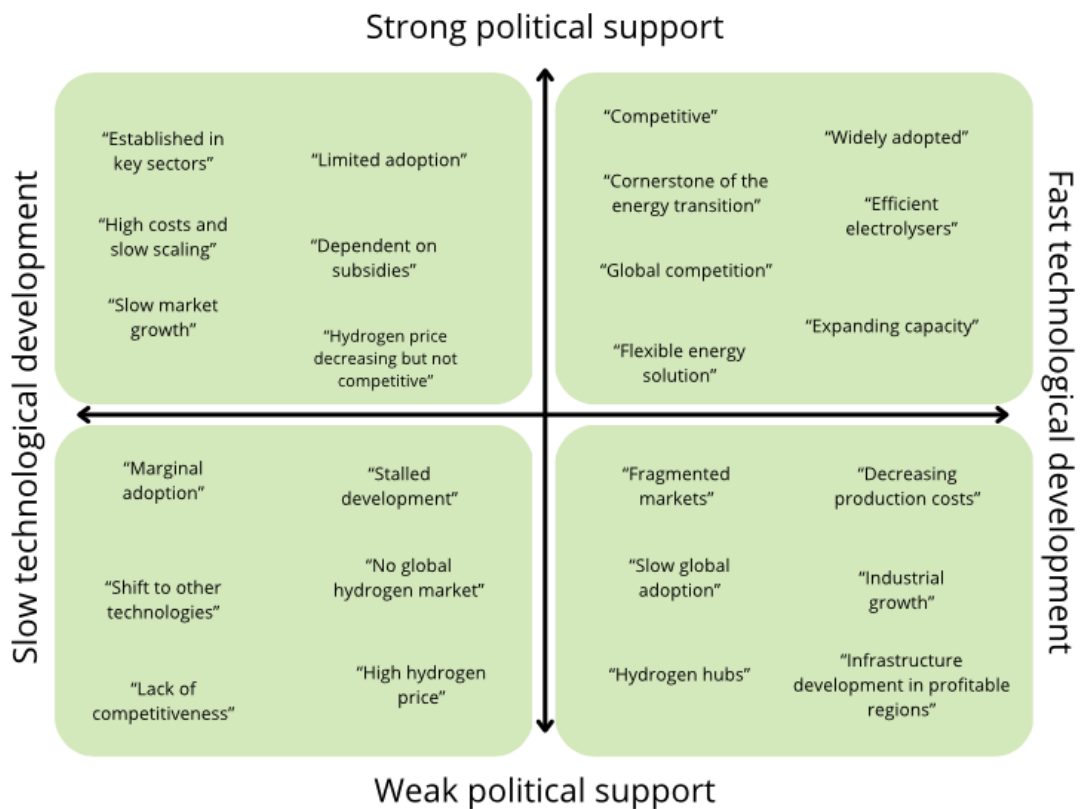
**Future vision 3:** (Weak political support – Fast technological development)

The production costs of green hydrogen have fallen significantly due to technological developments, but the market is fragmented. The production of green hydrogen is the responsibility of the private sector. Electrolyzer manufacturers have focused on cost-effective solutions, and new innovations are being developed. The availability of critical raw materials for alkaline and PEM electrolyzers has become more difficult due to weak political support, and alternative solutions have begun to be invented. The AEM electrolyzer is making a breakthrough in the market, as it does not depend on critical raw materials. Without strong political guidance, the deployment of hydrogen has depended on local market forces and there are significant hydrogen hubs in developed countries, but large-scale global deployment is slow. The use of hydrogen is growing, particularly in industry and as a flexible element in electricity systems, but its adoption in transport remains limited. Green hydrogen infrastructure is developing mainly in the most profitable regions. However, strong competition from battery technology is significantly slowing down the breakthrough of hydrogen in transport applications.

**Future vision 4:** (Weak political support – Slow technological development)

Green hydrogen has remained a marginal phenomenon, and its deployment is very limited. The development of electrolyzers has slowed down significantly, as investments have been directed towards other technologies, such as direct electrification and bioenergy. The alkaline electrolyzer is still mainstream, and the price of hydrogen is still

high, and it is not competitive with fossil fuels or grey hydrogen. Many companies that invested in hydrogen have shifted their resources to other technologies, and hydrogen investments have decreased significantly. China focuses mainly on its own needs, and dominates the hydrogen market, because Europe and the USA have lagged behind. Political support is weak and fragmented. Only individual countries are investing in hydrogen, but a large-scale international market has not emerged.



**Figure 8.** Future visions for 2030 presented in a four-field framework.

### 4.3 Scenarios for the future of green hydrogen

From the energy sector's perspective, the energy crisis of recent years and climate change are perhaps the most significant factors determining the future, and together they are accelerating the transition towards more sustainable energy sources. The further intensified cooperation of nations for the benefit of the climate with the Paris Climate Agreement gives reason to assume that more work will be done in the coming

years to mitigate climate change in all alternative futures. This has led to growing investments in renewable energy, energy efficiency and low-carbon fuels, such as green hydrogen. The current geopolitical situation is unstable and may slow down the green transition, especially in the United States, and thus also affects the entire world.

Based on the theoretical chapters two and three, it can be assumed that green hydrogen will be part of the solution to the energy crisis and climate change, as countries have invested heavily in the development of green hydrogen. The strength of political support and technological development will determine the timetable and strength of green hydrogen becoming part of the energy system and whether it will be used globally or only in certain regions. It can also be assumed that the production of renewable energy in the energy sector will increase, but its variability in production poses challenges for balancing the electricity grid. At the same time, the industry and transport sectors are looking for solutions to reduce their carbon dioxide emissions.

#### **4.3.1 The era of green hydrogen**

This first scenario, “The era of green hydrogen”, describes the pathway from the present year 2025 to the first future vision for 2030 (chapter 4.2.4). This scenario describes to a situation where green hydrogen has become one of the key cornerstones of the energy transition and is competitive with fossil fuels and grey hydrogen, and is also widely used by industry, transport and the energy sector. In this scenario, political support is strong and technological development is fast. The first step towards the green hydrogen revolution is to strengthen political support and increase investment. Currently, governments around the world have recognized the potential of hydrogen as part of the energy transition and climate goals, and they need to strengthen political support for green hydrogen even more and ensure that investments are made. The next task for governments is to create stable and predictable conditions for the development of hydrogen production and infrastructure, which requires long-term and binding political decisions, financing mechanisms and regulations that support investments and the scaling up of the technology. National hydrogen strategies are more detailed, and

different regions are setting their own development and financing priorities how to proceed in the field of green hydrogen, for example whether to focus on importing or exporting green hydrogen. Clear prioritization helps guide investments, accelerate technology adoption, and ensure efficient allocation of resources (IRENA, 2024). It also promotes cost reduction, scaling, and stakeholder coordination, which strengthens the development and competitiveness of the hydrogen sector (IRENA, 2024).

In Europe, green hydrogen targets and legislation will be clarified and strengthened. The targets of the REPowerEU -program will be updated to be more ambitious and its role in the EU's energy and climate policy will be strengthened. The regulatory framework for hydrogen production and use will be harmonized to reduce investment risks. The hydrogen guarantee of origin system will be more widely deployed to enable companies to ensure the greenness of hydrogen and benefit from incentives. The European Union and its member states will increase their investments in different areas of green hydrogen, such as its production, research and development, infrastructure and distribution. The number of final investment decisions in green hydrogen will increase significantly. The projects that should be operational in 2030 should receive their final investment decisions (FID) in 2025–2027 (European Court of Auditors, 2024). Europe will develop a plan for hydrogen infrastructure and start building it, especially in industrial clusters and ports. Hydrogen valleys have been identified as an important factor in creating a successful hydrogen economy in Europe (Clean Hydrogen Partnership, n.d.).

Green hydrogen production has become a key part of the global energy transition, but its development in the United States has been heavily dependent on political decisions. While the new Trump administration initially focused on supporting fossil fuels, economic and geopolitical realities have begun to change the situation. International competition, importance of energy self-sufficiency, and pressure from large investors and corporations have made green hydrogen an inevitable part of US energy policy. Several global companies and investors, committed to ambitious carbon neutrality goals, are demanding for stronger political support for renewable energy sources, including

green hydrogen. These actors see green hydrogen as a key means of achieving their climate goals, and their investments are now also shaping the national energy policy discourse. At the same time, the European Union and China have maintained consistent political support for climate action, which has enabled steady progress in green hydrogen technologies and infrastructure. The United States, on the other hand, has taken a step back in climate policy by 2025 under the Trump administration, which has weakened its international competitive position in this field. As the global competition for green hydrogen leadership intensifies, the United States is now at a disadvantage. However, this increasing pressure is progressively contributing to a shift in policy orientation. Several states and large private companies have independently promoted green hydrogen projects, which has increased domestic momentum. The demand generated by these regional and private initiatives has become so significant that the federal government can no longer ignore it. Geopolitical interests and the need to stay involved in the international hydrogen economy have led the federal government to look at green hydrogen in a new light. Although the government initially did not actively support the development of green hydrogen, it has now begun to respond. The Department of Energy and the Environmental Protection Agency have begun to prepare green hydrogen production standards. At the same time, the US hydrogen economy strategy is being updated, the goals are made more ambitious and the priorities for the states are being clarified. As the efficiency, sustainability, and cost of electrolyzers improve, the price of green hydrogen is expected to fall to 2 dollars per kilogram by 2026. This economic competitiveness, combined with international pressure and domestic innovation, will accelerate the transition. Political support for green hydrogen in the US is growing stronger, but due to its weak starting position, the US hydrogen economy may still struggle to reach the same level of development as in Europe and China.

China will publish new goals and a strategy for green hydrogen production and the systematic increase of fuel cell vehicles. China has achieved the 2025 goals set for green hydrogen production and transportation and will gain a head start in hydrogen-powered vehicles. In China, there are differences between provinces in the deployment of green

hydrogen, with some provinces setting targets even exceeding national targets. In addition, China is investing in scaling up and mass-producing electrolyzers to reduce production costs and produce the cheapest electrolyzers and would strive to maintain its position as leading player in hydrogen production.

Once political support and funding are secured, the next focus will be on developing electrolyzer technology, scaling it up and building infrastructure. Improving the performance of electrolyzers and optimizing larger-scale production of green hydrogen are critical to bringing hydrogen production costs competitive with fossil fuels (IRENA, 2020a). The solid oxide and AEM electrolyzers have also emerged on the market as competing technologies with alkaline and PEM electrolyzers. Significant improvements are being made at the system level in electrolyzer technologies, such as efficiency, current density, and start-up time. However, the material challenges of PEM and alkaline electrolyzers are slower to resolve. The development of new materials is slowed down by durability tests, which can last for thousands of hours or even several years (IRENA, 2020a). For this reason, the AEM electrolyzer is emerging as the strongest competitor to the PEM electrolyzer, as it is not dependent on expensive raw materials. However, accelerated testing of electrolyzers can reduce durability tests to just a few weeks or months (Hubert et al., n.d.). These accelerated tests could be the key to the competitiveness of PEM electrolyzers, enabling a faster transition away from expensive and rare raw materials, such as iridium and platinum, sooner than previously expected. Additionally, the high initial investment costs of solid oxide electrolyzers have been reduced, and their durability has been improved.

Industry has begun to widely use hydrogen in steel production, ammonia and methanol production, and in heavy industry, where it replaces natural gas and coal. In the transport sector, the hydrogen refueling network is expanding, and heavy-duty vehicles are using fuel cells and liquid hydrogen. Maritime transport is switching to fuels produced from hydrogen, such as ammonia and methanol, and aviation is starting to use synthetic fuels. Hydrogen storage will become a key part of the energy system, balancing fluctuations in

energy production and consumption. The integration of renewable energy and the hydrogen economy will enable the stabilization of electricity grids without traditional fossil-fueled backup power plants. At the same time, the global hydrogen market is becoming established, and competition between Europe, the United States and China is accelerating technological innovation. In addition, the introduction of green hydrogen is also enabled in developing countries where there are good solar or wind power potential. As green hydrogen begins to achieve global adoption, it will also be important to create common rules and standards for its production and use. Common regulations and standards are being prepared.

By 2030, the hydrogen economy has become one of the key cornerstones of the energy transition. It has been integrated into energy production, industry and transport, which has enabled a significant reduction in carbon dioxide emissions worldwide. The development of the hydrogen economy has not been linear, but has required strong political guidance, technological progress and the development of market mechanisms. Without strategic investments from governments and companies, the growth of the hydrogen economy would have been slower. Now hydrogen is an established part of the global energy system and contributes to achieving carbon neutrality. The hydrogen economy is no longer a technology of the future, but a permanent part of a sustainable energy system.

#### **4.3.2 Green hydrogen economy without innovation**

This scenario, “Green hydrogen economy without innovation”, describes the pathway from the present year 2025 to the second future vision for 2030 (chapter 4.2.4). In this scenario green hydrogen has received strong political support, but slow technological development is holding back the green hydrogen market and large-scale deployment. The hydrogen economy is moving from concept to large-scale implementation, and political support for green hydrogen is strong. Europe and China are committed to the large-scale deployment of green hydrogen as part of the energy transition. The US government's support for renewable energy and thus green hydrogen has also begun to

strengthen, as pressure from industry and investors on the government is increasing. Strong political support is also needed from the government. Global competition with China and the EU is intensifying, and governments in these regions are increasing their investments together with private companies. This also forces the US government to support the development of green hydrogen in order to keep the country in the economic competition and strengthen its energy independence. International and national financing mechanisms, such as the European REPowerEU, the United States Inflation Reduction Act (IRA) and Chinese government support programs, are channeling big investments into the hydrogen economy.

Despite strong political decisions and funding, technological development is progressing slowly. The cost of electrolyzers is decreasing only slightly, and efficiency improvements are limited. Certain electrolyser technologies, such as solid oxide electrolysis (SOE) and anion exchange membrane electrolysis (AEM), have not reached commercial maturity. In turn, PEM electrolyzers are still expensive and dependent on rare materials, so alkaline electrolyzers continue to dominate. Governments are providing significant subsidies for the development of hydrogen economy infrastructure, and hydrogen projects are progressing rapidly. Numerous electrolyser plants are under construction, but technological development has not met expectations. The availability of electrolyzers is limited, their service life is short, and high operating costs make it difficult for hydrogen to compete with fossil fuels. Green hydrogen production capacity is increasing, but efficiency issues, material costs, and availability of raw materials limit a significant increase in production volumes. At the same time, the hydrogen economy has not been able to scale as expected, leading to bottlenecks in energy networks and logistics. Although there is heavy investment in hydrogen storage and distribution, technological constraints are preventing the development of efficient energy storage and transportation. Governments are starting to decide to set prices and tariffs on carbon emissions to make fossil fuels, such as grey hydrogen more expensive. This will make green hydrogen a more attractive option, although its price has not been sufficiently calculated due to the slow pace of technological development.

By 2030, political support for the hydrogen economy remains strong, but due to the slow development of technology, hydrogen has not yet achieved the expected competitiveness. Government support systems have kept the hydrogen economy viable, but without technological breakthroughs, the production costs of green hydrogen will remain high. The breakthrough for green hydrogen will be delayed until the next decade.

#### **4.3.3 Green hydrogen economy without political support as technology leads**

This scenario, “Green hydrogen economy without political support as technology leads”, describes the pathway from the present year 2025 to the third future vision for 2030 (chapter 4.2.4). In this scenario, political support is weak, but technological development is fast. The hydrogen economy has made significant technological progress, but political support is weak and inconsistent. Although research and development have produced significant breakthroughs in electrolyser technology, national commitment to promoting the hydrogen economy is variable. Many governments are focusing on other technologies, and the development of the hydrogen economy will depend on market forces and private investment.

The planning of new green hydrogen strategies will slow down, and national targets will remain the same, although technological potential could provide the keys to producing larger quantities of green hydrogen. Companies and individual regions will start to set their own more ambitious targets and green hydrogen production will thus become very regional.

The European Union's targets and investments in green hydrogen production are decreasing and some member states are moving to develop other technologies. Only some of the planned green hydrogen projects are being implemented, as weak political support is causing investors to back down. However, some member states are setting their own more ambitious targets and are incorporating green hydrogen into their own country's infrastructure, especially countries with a lot of potential for increasing solar and wind power. In the United States, support for renewable energy sources is also

weakening further and the government is withdrawing its promised support measures for green hydrogen production. US states are being given more power to decide on their own energy policy, which is causing major differences in terms of renewable energy and, consequently, green hydrogen production. Some states are setting their own support measures and targets for green hydrogen production, while others are focusing on fossil fuels or other technologies. Like Europe and the United States, China is also seeing a slowdown in investment and the government's new green hydrogen production targets are low. There will be significant regional disparities in China, with some regions developing green hydrogen production and deployment independently, while others will discontinue green hydrogen production due to a lack of significant investment and government support. Large regional disparities will lead to fragmented green hydrogen markets and a failure to achieve widespread global deployment.

The regulation of green hydrogen is in the early stages and different countries will have different standardizations. Differences in green hydrogen standards and regulations on how it can be produced create an imbalance in the market. Infrastructure construction is highly dependent on political support from governments, so its wider development remains incomplete. However, in areas where green hydrogen production is high, infrastructure is being built with the help of the private sector. This leads to large regional differences, in some countries green hydrogen has been widely adopted and is an important part of the energy transition, while in other areas the focus has been on other technologies.

The technical characteristics of electrolysis devices, such as efficiency, have improved significantly and new materials have begun to be tested, especially to replace expensive and rare raw materials. Solid oxide and AEM electrolyzers have both arrived on the market, and the AEM electrolyser is attracting a lot of attention because it does not require expensive raw materials. Raw materials are running out because political support has not been received and they are being diverted to other technologies. The critical raw materials used in PEM electrolyzers are mainly sourced from South Africa, while the

critical raw materials used in solid oxide electrolyzers are mainly sourced from China (IRENA, 2020a). Alkaline and AEM electrolyzers use more widely available and readily available raw materials, such as steel and nickel (IRENA, 2020a). In this scenario, technological progress in the development of electrolysis equipment does not receive sufficient political support. China consolidates its dominance in emerging solid oxide electrolyser technologies and the associated critical materials, while South-Africa retains control over key inputs for PEM electrolyzers, such as platinum and iridium. In contrast, the EU and the United States remain materially dependent and geopolitically vulnerable, having failed to leverage political instruments to secure access to essential raw materials despite their technological capabilities. Despite the lack of political support, companies and private investors are financing the development of the hydrogen economy. Innovation projects by large technology companies and energy producers are leading to rapid cost reductions in the production of green hydrogen. Private companies may also have developed new innovations and electrolysis technologies.

By 2030, the hydrogen economy will have made significant technological progress, but the lack of political support has slowed down its large-scale implementation. The reduction in technology costs has enabled the use of hydrogen in industry and energy production, but without state-supported infrastructure projects, the growth of the hydrogen economy has remained market-based and regionally uneven. The hydrogen economy has developed on the back of the private sector, but its full potential has not been exploited. Without clear political direction and regulation, the growth of the hydrogen market has not been sufficiently consistent, and some economies have left hydrogen-based solutions secondary to other energy solutions.

#### **4.3.4 From vision to lost opportunity in green hydrogen development**

This scenario “From vision to lost opportunity in green hydrogen development”, describes the pathway from the present year 2025 to the fourth future vision for 2030 (chapter 4.2.4). In this scenario, political support is weak and technological development is slow. The hydrogen economy is still in the planning stage, and both political support

and technological development are progressing slowly. Although ambitious goals have been set for the hydrogen economy, practical actions and final investments have been limited. Government policies are inconsistent and long-term commitments have not been made. Companies are hesitant to invest on a large scale due to the uncertain regulatory environment and the lack of support mechanisms for the hydrogen economy. Technological development is progressing slowly, and there have been no major breakthroughs in electrolyser technologies. AE and PEM electrolysers are still the most widely used electrolysers, but their efficiency has not improved significantly. Solid oxide and AEM electrolysers are still in the development stage and have not become competitive options for large-scale hydrogen production. Production costs remain high, and green hydrogen is not competitive with fossil fuels. The growth of the hydrogen economy is slow and fragmented without political incentives and investments are occasional and mostly at the level of pilot projects. Industrial interest in the hydrogen economy is weak, because costs are still high and there are insufficient market incentives to use hydrogen instead of fossil fuels. In transport, hydrogen infrastructure is developing slowly, and the hydrogen refueling station network remains limited.

By 2030, the hydrogen economy has remained a marginal phenomenon and has not become a significant part of the global energy system. Due to weak political support and slow technological development, hydrogen has not achieved competitiveness compared to fossil fuels. Large industries have switched to other low-carbon solutions, and hydrogen use has remained small-scale. Industry has not adopted hydrogen widely, and hydrogen has remained of little importance in the transport sector. Biofuels and battery technology are strong options as low-carbon solutions in the transportation sector. The introduction of biofuels does not require modifications to vehicles and can be used in existing infrastructure, and in turn, electric vehicles are zero-emission, and their use effectively helps to decarbonize the transport sector (Sandaka & Kumar, 2023). Without significant technological advances, hydrogen production has remained expensive, and the infrastructure has not been built comprehensively. The potential of the hydrogen economy has not been fully exploited, and the market has developed only slowly without

a coherent strategy or international agreements. The hydrogen economy has remained a small-scale and local phenomenon. The market has developed only where private investors have taken the hydrogen economy into their own hands, but large-scale transformation has not materialized. The hydrogen economy has not completely disappeared, but it has lost a significant opportunity to become one of the key cornerstones of the energy transition. Without technological breakthroughs and political support, hydrogen has not been able to emerge as a competitive alternative, and the energy transition has taken place with other solutions. This scenario shows that without a clear strategy and strong technological development, the growth of the hydrogen economy may stop before it reaches its full potential.

#### **4.3.5 Summary of scenarios**

The goal of this scenario analysis was to identify the key uncertainties affecting the future of green hydrogen, to understand how major political and technological uncertainties shape different possible futures and how these uncertainties are interdependent, and to explore the potential role of green hydrogen in these futures.

The development of green hydrogen is influenced by several political and technological uncertainties. Political uncertainties include the level and strength of public investments and subsidies, such as national hydrogen strategies, tax incentives, and direct financial support for green hydrogen projects. Another key political factor is carbon pricing, which improves the competitiveness of green hydrogen compared to fossil fuels and grey hydrogen. Carbon pricing is particularly important in scenario where political support is strong but technological development is slow for the price of green hydrogen cannot be sufficiently reduced through technological means, but pricing mechanisms like carbon taxes or tariffs can help balance the cost gap. Technological uncertainties mainly relate to the timing of electrolyser technology development. Although continuous progress in electrolyser technology is expected, the exact timing remains uncertain. It is unclear how quickly new technologies will enter the market and whether the currently dominant AE and PEM technologies will overcome their current challenges. In scenarios where

technological development is slow, AE and PEM electrolyzers are likely to remain the mainstream solutions. However, in scenarios of fast technological advancement, new competitors may emerge for instance, AEM electrolyzers could rise as challengers to PEM technology. In addition, developments in storage technologies and infrastructure, cost reductions, improvements in efficiency, extensions in operational lifetime, and reductions in the use of critical raw materials are also major uncertainties that will shape the future of green hydrogen.

Green hydrogen is expected to play a particularly significant role in the future energy system, especially in sectors where reducing emissions is challenging, such as the steel industry, chemical industry, heavy transport, and maritime shipping. To reach its full potential, green hydrogen will require strong political support through investments and regulation, fast technological development to lower costs and improve efficiency, and consistent support policies and infrastructure projects that enable large-scale deployment. Clear regulatory frameworks and harmonized standards are essential for steering green hydrogen production in the right direction and strengthening investor confidence. Global standards facilitate the international trade of hydrogen and promote the development of markets. Technological advancements support this process by reducing the costs of electrolyzers, improving their efficiency and operational lifetime, and decreasing dependence on critical raw materials. This also enables the broader development of storage technologies and infrastructure, making green hydrogen production more economically viable and scalable.

Green hydrogen can achieve competitiveness with grey hydrogen if strong political support is combined with rapid technological development, as these two factors are closely interdependent. For example, in a scenario where technological progress is rapid but political support is weak, green hydrogen production and use would remain a local phenomenon without extensive international trade. In such a situation, regulation and standardization would also remain fragmented, potentially leading to significant price disparities between different regions. The competitiveness of green hydrogen can be

strengthened through the declining cost of renewable electricity, reductions in electrolyser costs, the expansion of distribution and storage infrastructure, the implementation of effective carbon pricing mechanisms, and the pursuit of consistent and long-term policy frameworks.

## 5 Discussion and Conclusions

Green hydrogen has gained significant attention in recent years as a solution for reducing emissions, enhancing energy security, and developing sustainable industry. This thesis examined the electrolysis technologies used in green hydrogen production and compared their benefits and challenges. It also provided an overview of the green hydrogen policies and regulations in the European Union, the United States, and China. In addition, four different scenarios were developed to assess the potential role of green hydrogen in the future energy infrastructure and to understand different possible development paths.

Green hydrogen faces several challenges, it is still expensive to produce, the market is not fully developed, and the infrastructure for distribution and storage is limited (IRENA, 2020a). As renewable electricity gets cheaper, the focus is shifting to making electrolyzers more affordable and efficient (IRENA, 2020a). This includes better design, scaling up production and using less expensive materials (IRENA, 2020a). Currently, there is no single electrolyser technology that stands out across all key aspects, but different technologies offer their own strengths (IRENA, 2020a). Alkaline electrolyzers are cost-effective and technologically mature, but they face challenges such as low current density and efficiency (Guo et al., 2024; IRENA, 2023). In addition, they are not optimally suited for integration with variable renewable electricity generation, such as solar and wind power (Akyüz et al., 2024). PEM electrolyzers offer higher current densities and efficiencies but are still heavily dependent on expensive catalyst materials (Akyüz et al., 2024). Currently, alkaline electrolyzers are the most widely used, followed by PEM electrolyser technology (IEA, 2024). AEM and solid oxide electrolyzers are not yet on the market to a significant extent (Ikuerowo et al., 2024). AEM electrolyser technology is considered a potential competitor to PEM electrolyzers, as it does not require valuable catalysts and is therefore more cost-effective (Akyüz et al., 2024). On the other hand, AEM electrolyser technology is still in the development phase and faces challenges, especially in terms of lifetime and efficiency (Ikuerowo et al., 2024). Solid oxide

electrolysers offer the highest efficiency, but their high operating temperature places significant demands on the durability of the materials (Akyüz et al., 2024).

National strategies and roadmaps for green hydrogen have increased significantly in recent years, and green hydrogen is seen in the strategies to achieve net-zero decarbonization goals, improving energy security and green industrial development (IEA, 2024). The European Union has set targets for green hydrogen production volumes and installed electrolysers (European Commission, 2020). In addition, the EU has updated its Renewable Energy Directive and delegated acts related to green hydrogen production and the calculation of green hydrogen life cycle greenhouse gases (European Court of Auditors, 2024; European Commission, 2023/1184; European Commission, 2023/1185). The European Union also has various financing mechanisms, such as The European Hydrogen Bank and Horizon Europe (European Commission, n.d.-c; European Commission, n.d.-f). In turn, the political situation in the United States regarding renewable energy and thus also green hydrogen is uncertain and difficult to predict. The US Green Hydrogen Strategy and Roadmap set targets to increase the production volume and reduce the price of green hydrogen (U.S. Department of Energy, 2023). However, the United States does not yet have a comprehensive regulatory framework for green hydrogen production, even though rules for calculating its lifecycle emissions have been established. In addition, the United States has allocated funding for green hydrogen hubs, electrolysis technology development, green hydrogen production, and recycling programs (U.S. Department of Energy, 2024). Green hydrogen producers are also eligible for tax incentives (U.S. Department of Energy, 2025). Several states also have their own forms of support and funding programs to promote green hydrogen (Bade & Tamomewo, 2024). China has also introduced many new policies related to green hydrogen (Zhang, 2024). The production volume targets set in China are more moderate than in the European Union or in the United States, because of previous overproduction situations, such as those experienced in the solar and battery sectors (Miller-Wang, 2023). China has also set targets to increase the use of green hydrogen in transport (IEA, 2023). In addition, China's hydrogen strategy has focused on developing standards and safety

across the entire value chain (IRENA, 2024). China has provided significant funding especially for fuel cell vehicles, and local governments have also supported projects related to the hydrogen economy (Dellatte, 2023; Miller-Wang, 2023).

The scenario analysis demonstrated that political support and technological development are closely interconnected. By varying the level of political support (strong to weak) and the speed of technological development (fast to slow), four different scenarios and future visions for the year 2030 were created. In the scenario where political support is strong and technological development is fast, these factors reinforce each other and accelerate the development and adoption of green hydrogen in a positive way. The cost of electrolysis technologies decreases, making green hydrogen more competitive with fossil fuels and grey hydrogen. In the scenario with strong political support but slow technological development, the adoption and expansion of green hydrogen are delayed. Here, the importance of government support is emphasized, and the progress relies heavily on public funding and regulation. If political support is weak but technological development is fast, the leadership shifts to the private sector. However, without sufficient public support and international coordination, global adoption and market expansion of green hydrogen remain limited. In the fourth scenario, where both political support and technological development are weak, green hydrogen becomes a brief phenomenon. Its high production costs, inefficient electrolysis technologies, and lack of infrastructure prevent any meaningful large-scale deployment. Although the same uncertainties were applied to the US, EU, and China in all scenarios, some differences emerged due to the current geopolitical context. Progress on renewable energy in the United States may face challenges, as the country has withdrawn from the Paris Climate Agreement and the new federal administration is introducing obstacles such as halting wind energy leasing and permitting, freezing funding, and threatening to dismantle key legislation like the Inflation Reduction Act and the Bipartisan Infrastructure Law (Bird et al., 2025; European Parliament, 2025). Therefore, even in a scenario like "The Era of Green Hydrogen", where political support is strong across all regions, the US starts from a different position, because they are

currently falling behind the EU and China in building a competitive hydrogen economy. Based on the material reviewed in the study and the current uncertain geopolitical situation, the most likely development scenario for the United States appears to be a "Green hydrogen economy without political support as technology leads". This is based on the fact that the new administration has made significant decisions not to support renewable energy sources, which has weakened the political position of green hydrogen. Despite this, there are several large international companies operating in the United States that recognize the benefits of renewable energy sources and thus the potential of green hydrogen, and it could be assumed that the development of green hydrogen will continue with the help of the private sector and research organizations.

For the European Union and China, the current geopolitical situation may slow down the focus on green hydrogen to some extent, but the likely scenario is still "The Era of Green Hydrogen". In Europe, significant investments have been made in green hydrogen, and several regulations have been adopted at the EU level to promote it. China, on the other hand, already has a strong position in the manufacture of electrolyser technology, and the country is striving to maintain this competitive advantage by further strengthening the development of green hydrogen.

This study was limited to focus more on the technological and political implications for green hydrogen. Less attention was paid to economic, social and environmental aspects. Although the future of green hydrogen is strongly influenced by technological development and political support, a more thorough analysis would have required also examining, for example, the future of the green hydrogen market or environmental impacts. This limits the extent to which the findings can be applied, especially when assessing the implementation of a hydrogen economy in a complex, multi-impact social environment. The method used in this study also imposes limitations, as scenario work is always tied to the values, perceptions, and future visions of its author, which affects the types of alternative development paths that are identified. The limitations of scenario work are particularly emphasized in rapidly changing social situations, as

continuous and unpredictable changes in the operating environment, such as new innovations, globalization, changes in values and attitudes, and economic cycles, can quickly make the original scenarios obsolete (Rubin, 2004). Based on this, the following further research suggestions could be made. Further research ideas could include economic and market analysis of how to enable global hydrogen trade. What problems could be encountered in transporting green hydrogen and building infrastructure and what is required to enable international hydrogen export and import. Also, ideas for further research could be the environmental impacts of green hydrogen production, such as water consumption in production, as well as life cycle assessments of various electrolysis devices and their sustainability assessment. It would also be good to study the safety risks associated with the production, transportation and use of green hydrogen more before its deployment is expanded.

The main conclusions of this study are as follows:

- The production of green hydrogen is still expensive and therefore requires technological development and strong political support.
- National green hydrogen strategies and roadmaps have increased significantly in recent years, and green hydrogen is seen particularly as a solution to achieving carbon neutrality.
- The future of the hydrogen economy depends on how political support and technological development meet and how well they can promote each other.
- Without strong political support from governments, the hydrogen economy may remain local.
- Without fast technological development, using green hydrogen widely in various sectors remains limited and is likely to be delayed.

Based on this study, the following guidelines are given to a company manufacturing low-voltage products:

- Projects aiming for completion by 2030 should reach a final investment decision within the next years. The timing and number of these decisions can also indicate how strongly green hydrogen is likely to be adopted in the future.
- It is important to closely follow technological breakthroughs in the development of electrolysis equipment and observe what new technologies enter the market, as these innovations will shape the competitiveness and scalability of green hydrogen production in the future.
- Track developments in PEM electrolyser technology aimed at reducing dependence on expensive and scarce raw materials, such as platinum and iridium, as this will be critical for cost reduction and large-scale scalability.
- Track progress on national green hydrogen production targets, as deviations from set targets may signal broader structural or policy challenges. For example, the EU has not met its 2024 targets, raising questions about the feasibility of similar targets elsewhere, such as China's 2025 targets.

## 6 Summary

This thesis began by outlining the key concepts relevant to the study, with particular focus on green hydrogen and electrolyser technologies. It proceeded to analyze the current state and major challenges associated with green hydrogen development, presenting an overview of the main electrolyser technologies, including their respective advantages and limitations. The integration of electrolysis systems with renewable energy sources, such as wind and solar power, was also examined. In addition, the thesis provided a comparative overview of green hydrogen strategies in the European Union, the United States, and China. Particular attention was given to the regulatory frameworks in place or under development in these regions, as well as to the various governmental initiatives aimed at supporting the adoption of green hydrogen technologies.

The green hydrogen is seen as one of the key solutions in the energy transition, but its future depends significantly on two factors: strength of political support and timing of technological development. By examining four different scenarios, we can understand how these factors affect the development of the green hydrogen and its potential to become a large-scale part of the global energy system. In addition, scenarios can help an organization make decisions in an uncertain operating environment, identify potential risks and opportunities, and prepare for different future developments. Scenarios can help an organization develop more flexible strategies and improve decision-making in the long term.

In the first and most optimistic scenario, political support is strong and technological development is fast. In this scenario, governments make long-term decisions that support the growth of the hydrogen economy, while at the same time electrolyser technology and infrastructure develop fast. This enables the rapid spread of green hydrogen in industry, transport and energy production, making it a truly competitive alternative to fossil fuels. The hydrogen economy will become one of the cornerstones of the energy transition. The second scenario, where political support is strong but

technological development is slow, shows that even if investments are made, the growth of the hydrogen economy may be slow. Without technological breakthroughs, the costs of electrolyzers and hydrogen production costs will remain high, which will slow down its deployment. This means that the hydrogen economy will develop, but it will remain dependent on subsidies for a longer period than in the optimistic scenario. In the third scenario, where political support is weak but technological development is fast, the hydrogen economy will progress under market conditions. New technological solutions will reduce the costs of hydrogen production and improve its competitiveness, but without political support mechanisms, infrastructure development will be slow, and the hydrogen economy will spread unevenly. This may lead to a situation where hydrogen becomes widespread only in certain areas where the private sector is willing to invest, while in other areas it will remain marginal. In the fourth and most pessimistic scenario the political support is weak and technological development is slow. In this scenario, the hydrogen economy will not develop significantly, because without investment and technological innovation, the costs of hydrogen will remain high, and the infrastructure will not develop. This will lead to a situation where the hydrogen economy will remain small-scale and other low-carbon solutions, such as electrification and bioenergy, will crowd it out in the energy market.

The results of the study show that green hydrogen production is still expensive, and reducing costs requires both strong political support from governments and the development of electrolyser technologies. The number of national hydrogen strategies has increased significantly in recent years, and green hydrogen is considered a key means of achieving carbon neutrality goals. The timing and extent of green hydrogen deployment in different sectors depends not only on the strength of political support and the speed of technological development, but also on the combined effect of these factors. If political support remains weak, there is a risk that green hydrogen development will be concentrated only in certain areas, where, for example, the private sector actively invests in its production and deployment. On the other hand, if technological development is slow despite political support, green hydrogen will remain

heavily dependent on subsidies, its deployment in different sectors will be limited, and large-scale use will be delayed.

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