THE ROLE OF GREEN HYDROGEN IN EUROPE'S ENERGY TRANSITION

Lappeenranta–Lahti University of Technology LUT

Master's thesis in Circular Economy

2026

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Examiners: Professor (tenured) Jouni Havukainen

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ABSTRACT

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The role of green hydrogen in Europe's energy transition

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54 pages, 5 figures and 7 tables

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Keywords: green hydrogen, European Union, energy transition, electrolysis capacity, hydrogen policy, renewable electricity, emission reductions

This master's thesis examines the role of green hydrogen in the European Union's (EU) energy transition and the opportunities and challenges related to its use. Green hydrogen is produced through electrolysis using renewable electricity, resulting in near-zero direct carbon dioxide (CO_2) emissions. The work focuses on the EU's regulatory and policy framework, support mechanisms and Member States' hydrogen strategies, with a closer examination of four front-runner countries in green hydrogen development: Germany, Spain, the Netherlands and Sweden. The main objective is to assess how green hydrogen can support the achievement of climate targets in the EU and what impacts expanding its production may have, especially on electricity consumption and emission reductions.

The thesis was conducted as a literature review based on EU documents, reports and scientific publications. A scenario-based calculation framework was developed for the selected front-runner countries to estimate the additional electricity demand to meet national electrolysis capacity targets, hydrogen production volumes, and greenhouse gas (GHG) emission reduction potential assuming that fossil-based grey hydrogen is replaced by green hydrogen at the EU level.

The results show that green hydrogen plays an important role, especially in hard-to-electrify sectors, such as emission-intensive industry and heavy-duty transport. However, the overall emission reduction potential remained relatively small. Large-scale deployment of green hydrogen requires substantial investments, hydrogen infrastructure, and coordinated EU level policies to meet the 2030 climate targets.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUT energiajärjestelmien tiedekunta
Ympäristötekniikka

Emmi Nylund

Vihreän vedyn rooli Euroopan energiasiirtymässä

Ympäristötekniikan diplomityö
2026
54 sivua, 5 kuvaa ja 7 taulukkoa
Tarkastajat: Professori (vakinainen) Jouni Havukainen ja nuorempi tutkija Ursula Salakka
Avainsanat: vihreä vety, Euroopan Unioni, energiasiirtymä, elektrolyysikapasiteetti, vetypolitiikka, uusiutuva sähkö, päästövähennys

Tässä diplomityössä tarkastellaan vihreän vedyn roolia Euroopan Unionin (EU) energiasiirtymässä sekä sen käyttöön liittyviä mahdollisuuksia ja haasteita. Vihreä vety tuotetaan elektrolyysillä uusiutuvaa sähköä käyttäen, eikä sen tuotannossa synny suoria hiilidioksidipäästöjä. Työssä keskitytään EU:n vihreää vetyä koskevaan sääntely- ja politiikkakehykseen, tukimekanismeihin sekä jäsenmaiden vetystrategioihin. Jäsenmaista valittiin tarkempaan tarkasteluun neljä vihreän vedyn kehityksen edelläkävijämaata: Saksa, Espanja, Alankomaat ja Ruotsi. Työn päätavoitteena on arvioida, miten vihreä vety voi tukea EU:n ilmastotavoitteiden saavuttamista ja millaisia vaikutuksia sen tuotannon laajentamisella voi olla erityisesti sähkönkulutukseen ja kasvihuonekaasupäästöihin (KHK).

Työ toteutettiin kirjallisuuskatsauksena, jossa hyödynnettiin EU:n virallisia asiakirjoja, raportteja sekä tieteellistä kirjallisuutta. Valituille edelläkävijämaille laadittiin yksinkertaistettu laskentamalli, jolla arvioitiin maan elektrolyysikapasiteettitavoitteen vaatimaa lisäsähkön tarvetta, vedyn tuotantomääriä sekä KHK-päästöjen vähennyspotentiaalia tilanteessa, jossa harmaa vety korvataan vihreällä vedyllä EU-tasolla.

Tulokset osoittavat, että vihreällä vedyllä on merkittävä rooli erityisesti vaikeasti sähköistettävillä sektoreilla, kuten päästöintensiivisessä teollisuudessa ja raskaassa liikenteessä. Kokonaisuudessaan päästövähennyspotentiaali jäi kuitenkin suhteellisen pieneksi. Lisäksi tulokset osoittivat vihreän vedyn laajamittaisen hyödyntämisen edellyttävän merkittäviä investointeja, vetyinfrastruktuurin kehittämistä sekä selkeää politiikkaa ja sääntelyä EU:n jäsenmaiden kesken, jotta vuoden 2030 ilmastotavoitteet voidaan saavuttaa.

ACKNOWLEDGEMENTS

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Helsinki, 5.2.2026

Emmi Nylund

SYMBOLS AND ABBREVIATIONS

Roman characters

E	electricity demand	[kWh, TWh]
m	mass	[kg, t, Mt]
e	electricity consumption	[kWh/kg]
P	power	[kW]

Abbreviations

AEL	Alkaline electrolysis
AEM	Anion exchange membrane electrolysis
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CEF	Connecting Europe facility
CF	Capacity factor
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EHB	European Hydrogen Backbone
EU	European Union
H_2	Hydrogen
IEA	International Energy Agency
IPCC	Intergovernmental panel on climate change
IPCEI	Important projects of common European interest
IRENA	International renewable energy agency
ISO	International organization for standardization
PEM	Proton exchange membrane electrolysis
RFNBO	Renewable Fuels of Non-Biological Origin
SOEC	Solid oxide electrolysis cell

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DECLARATIONS

Turnitin

The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of this thesis, Emmi Nylund, used the following AI-tools during the preparation of the thesis:

1. ChatGPT
    a. Purpose of the use: correcting grammar, searching information and translating the text
    b. Explanation of the use of the tool: ChatGPT has been used in this thesis to support the writing process by helping with grammar and translation between Finnish and English. ChatGPT was also used to search for academic sources and summarize key concepts.
2. MOT translator
    a. Purpose of the use: translating text
    b. Explanation of the use of the tool: MOT translator was used to translate text from Finnish into English.

Responsibility

The author, Emmi Nylund, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

The climate crisis has become one of the key drivers of change in the European energy sector. Reducing the use of fossil fuels and achieving climate goals will require major changes in both, production and consumption structures. To accelerate the energy transition, clean energy solutions are needed to replace the use of fossil fuels. These solutions must be suitable for sectors that are difficult to electrify, particularly in emission-intensive industries such as steel and chemical production as well as in heavy-duty transport. Various alternative energy sources have been developed to meet these needs, one of the most promising alternatives being hydrogen. (Sun et al. 2024.)

Hydrogen is the most abundant element in the world, but it does not exist as a pure substance. It is typically bound in compounds such as water or methane. Therefore, hydrogen must always be produced which makes it an energy carrier rather than a primary energy source. Hydrogen can be used as a fuel, raw material for industrial processes and as energy storage. Hydrogen has almost three times the energy content of gasoline or diesel, but its energy density is very low, making it difficult to store and transport. For this reason, hydrogen storage requires very high pressure, up to 700 bar. Alternatively, hydrogen can be converted to a liquid state by cooling it to -253°C. (Motiva 2025.)

Hydrogen can be produced through various methods, and its environmental impact depends on the chosen production pathway. The most common production methods include steam reforming of natural gas, gasification of coal or biomass, and electrolysis in which water is split into hydrogen and oxygen using electricity. Hydrogen produced through electrolysis using renewable electricity is referred to as green hydrogen, which can be considered as carbon-neutral and low-emission. (U.S Department of Energy n.d.)

In EU policy documents, green hydrogen is often referred to as renewable hydrogen or Renewable Fuel of Non-Biological Origin (RFNBO hydrogen), which must meet specific sustainability and life cycle emission criteria (R3 Sustainability 2025). The thesis examines the role of green hydrogen in Europe’s energy transition in more detail.

Governments, businesses, and investors around the world have committed to spend more than 500 billion dollars on more than 1000 hydrogen projects over the next few decades. (Sun et al. 2024.) Technological development and the decrease in the cost of renewable electricity have made the production of green hydrogen even more profitable. At the same time, the current world situation has highlighted the need to reduce Europe's energy dependency and develop its domestic energy potential. Green hydrogen is seen as a solution, and it supports both, climate goals and the reduction of dependence on energy imports. (Pepe et al. 2025.)

In this master’s thesis, the terms green hydrogen and renewable hydrogen are used interchangeably to describe hydrogen produced through electrolysis using renewable electricity. Also, the term Europe refers to the European Union and its Member States. The main objective of this master’s thesis is to examine the role of green hydrogen in the European energy transition and to assess the opportunities and challenges related to its production and utilization. This thesis provides an overview of the current situation of green hydrogen in the EU, including planned projects, support mechanisms and technological development, with a particular focus on countries where green hydrogen development has progressed the furthest.

The study analyses the current and near-future development of green hydrogen in selected EU Member States and examines how national hydrogen strategies, support mechanisms and policy frameworks influence its deployment. In addition, this thesis includes a simplified calculation to estimate electricity demand, hydrogen production volumes and potential GHG emission reduction related to planned electrolysis capacity in selected front-runner countries. The aim of this thesis is to provide a simplified comparison between countries to highlight the scale of renewable electricity and infrastructure required for green hydrogen development in Europe. The main research questions are:

1. What is the current state and expected development of green hydrogen in the European Union?
2. What opportunities and challenges are associated with the production and use of green hydrogen in Europe?
3. What is the emission reduction potential on EU level when selected front-runner countries replace grey hydrogen with green hydrogen?

The scope of this work covers the environmental aspects of hydrogen, focusing especially on GHG emissions from green hydrogen production. Other hydrogen production pathways are also briefly examined for comparative purposes. Geographically, the scope is limited to

Europe, and the examination focuses especially on the themes of industry, transport and energy storage.

The thesis is divided into seven main chapters. The first chapter introduces the objectives, research questions and scope of the work. The second chapter provides a background on green hydrogen and its role in the energy transition in the EU. The third chapter examines hydrogen-related strategies, policies and support mechanisms at the EU and selected Member States level. The fourth chapter presents the methodology, case area and calculation framework. The fifth chapter presents the results, opportunities and key challenges and delves deeper into the hydrogen strategies of front-runner countries. The sixth chapter discusses the findings and their implications. The seventh chapter summarizes the thesis and presents the main results and key conclusions.

2 Hydrogen in the European energy transition

Hydrogen is one of the energy carriers that are often considered to be enablers of sustainable energy systems (Ajanovic et al. 2024). Hydrogen is mainly used in oil refining and the production of ammonia and methanol (Statista 2026). Global hydrogen production was close to 100 million tonnes (Mt) in 2024, but less than one per cent of this production is still based on low- or zero-emission production methods. This indicates that the development of the sustainable hydrogen economy is still at an early stage and fossil-based production methods dominate the market. According to the International Energy Agency's (IEA) latest Global Hydrogen Review 2025 report, low-emission hydrogen production is expected to reach around 10 Mt by 2030. However, this expected growth is considerably lower than earlier estimates of up to 49 Mt, which indicates slower progress than previously anticipated. (IEA 2025a.)

In the EU, energy production and consumption account for a significant share of GHG emissions and are dependent on oil and gas imports. In July 2020, the European Commission highlighted the role of green hydrogen as a key element in accelerating the transition towards a climate-neutral energy system by 2050. In spring 2021, it was emphasized that green hydrogen based on renewable energy sources is the only solution that promotes climate neutrality in a sustainable way in the long term (European Parliament 2025).

In Europe, hydrogen is mainly linked to energy security and the flexibility of the electricity system. Green hydrogen can be utilized as an energy source or raw material, especially in industrial and chemical industry processes, as well as in aviation and maritime transport, where decarbonization is technically challenging or economically unviable with direct electrification. In addition, green hydrogen can act as an energy storage and help to balance the electricity system when renewable power production is low, for example, due to wind or solar conditions. (European Court of Auditors 2024.)

According to recent EU hydrogen market data, total hydrogen production in Europe amounted to approximately 11.2 Mt in 2024 and remained largely unchanged compared to 2023. Nearly 10 Mt of this production was from fossil-based pathways, mainly through reforming. This indicates that fossil-based hydrogen production has remained relatively stable and continues to dominate the market. (European Hydrogen Observatory 2026.) In contrast, electrolysis capacity has started to grow more rapidly. Installed electrolysis capacity reached around 376 MW by the end of 2024 and increased approximately to 571 MW by June 2025. This corresponds to an estimated annual production of about 94 kt of hydrogen (H_2). Around 288 MW of new capacity was installed within one year, increasing the available electrolysis capacity by about 1.5 times. According to current project plans, an additional 2.8 GW of electrolysis capacity is expected to be deployed by 2028. However, the EU has a target of reaching approximately 50 GW of electrolysis capacity by 2030, meaning that an additional 2.8 GW would still represent only a small share of the target. (European Hydrogen Observatory 2025a, Hydrogen Europe 2025.)

Although electrolysis capacity has increased significantly between 2024 and 2025, the total installed capacity level remains relatively small compared to the EU’s 2030 target of 50 GW. In addition, the capacity deployment is unevenly distributed across Europe. Figure 1 illustrates the differences in electrolysis capacity and deployment among the ten European countries with the highest installed capacity.

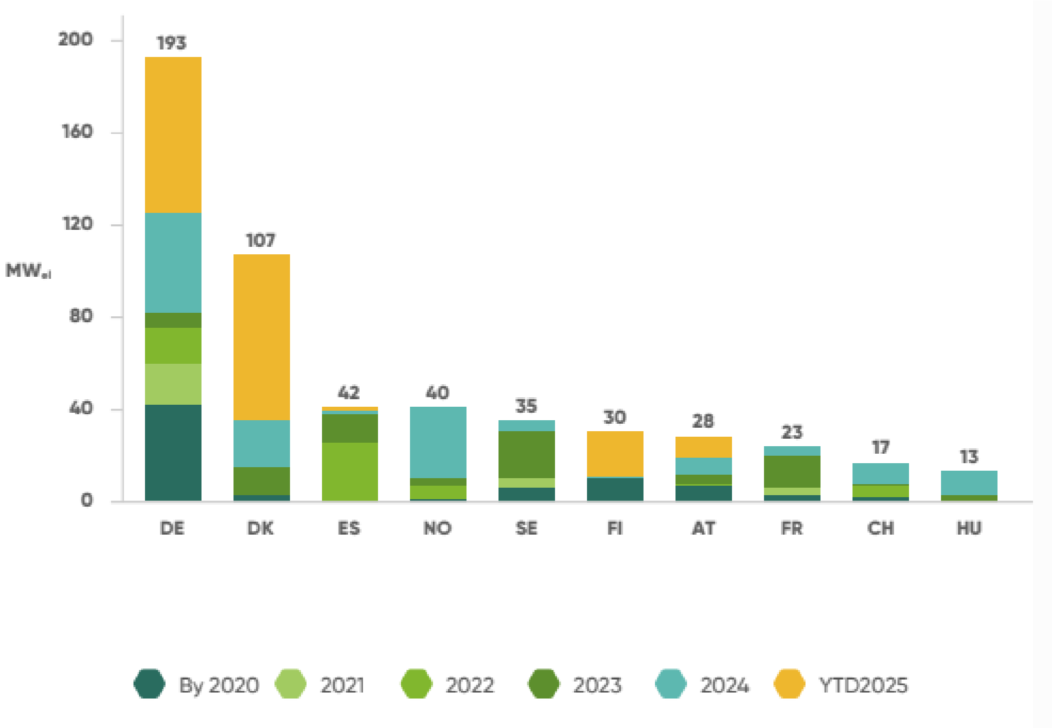

Figure 1. Installed and operational electrolysis capacity in European countries 2020 – June 2025. (Hydrogen Europe 2025.)

As shown in figure 1, Germany has the highest installed electrolysis capacity, followed by Denmark, while other countries operate at a considerably smaller scale. Many of the currently operating projects are pilot or early-stage commercial installations, typically located near existing industrial sites. This suggests that early green hydrogen deployment in Europe is closely linked to decarbonizing existing fossil-based hydrogen consumption. (Hydrogen Europe 2025.)

The following chapters explore in more detail the different hydrogen production methods and how they vary in terms of CO_2 emissions. Also, the role of green hydrogen in achieving the EU's climate goals, its role in the energy system, and its alignment with sustainability criteria will be discussed.

2.1 Hydrogen production technologies

Current hydrogen production is still largely based on fossil raw materials, which cause significant CO_2 emissions. Global hydrogen production has increased close to 100 Mt, but more than 95 % of this production is still mainly from natural gas and coal. As a result, hydrogen production is associated with substantial annual CO_2 emissions. (IEA 2025a.)

According to earlier IEA estimates about 830 Mt of CO_2 emissions are generated annually from the production of fossil-based hydrogen. Most of these emissions end up in the atmosphere, but about 130 Mt of CO_2 is recovered and used in the production of urea fertilizer. (IEA 2019.)

Hydrogen is commonly classified according to the CO_2 emissions associated with its production process using color-based terminology. Table 1 below presents the different hydrogen colors, their main production methods, energy sources and indicative emission levels based on life cycle considerations.

Table 1. Overview of hydrogen production methods. (Modified into table form from National Grid 2023).

Colour	**Production method**	**Energy source**	**Indicative emission level**
Green	Electrolysis	Renewable energy	Low life cycle CO_2 emissions
Blue	Steam reforming + CCS	Natural gas + carbon capture and storage	Some CO_2 is produced but a portion is captured
Grey	Steam reforming without CCS	Natural gas	High CO_2 emissions
Black/brown	Gasification	Coal (black), peat (brown)	Very high CO_2 emissions
Pink	Electrolysis	Nuclear energy	No direct emissions but nuclear-specific considerations
Yellow	Electrolysis	Grid electricity or solar power	Emissions depend on the origin of the electricity
Turquoise	Methane pyrolysis	Natural gas + low-carbon energy	Emissions can be low if carbon is stored
White	Naturally occurring hydrogen	Geological sources	No production emissions, but currently limited use

As seen in table 1, hydrogen is categorized based on its production method and the primary energy source used. The environmental impact of hydrogen depends on these production pathways. Currently, grey hydrogen is the most commonly used hydrogen in the energy industry, but some fossil-based production methods may lose relevance as efforts to reduce dependence on fossil fuels increase. Therefore, hydrogen’s contribution to carbon neutrality depends largely on the way it is produced. (National Grid 2023.)

Green hydrogen refers to hydrogen produced using renewable electricity and is associated with low life cycle CO_2 emissions. Green hydrogen is produced by electrolysis, where water is broken down by electric current into hydrogen and oxygen. When electricity used in electrolysis is produced entirely from renewable energy sources, the process itself is practically emission-free and enables a significant reduction in CO_2 emissions compared to fossil production methods. Nevertheless, small life cycle emissions may arise from the construction of renewable energy infrastructure and electrolysis equipment. Key technologies for green hydrogen production include:

1. Alkaline Electrolysis (AEL)
2. Proton Exchange Membrane Electrolysis (PEM)
3. Solid Oxide Electrolysis (SOEC)
4. Anion Exchange Electrolysis (AEM).

AEL and PEM electrolysis currently account for all installed capacity, while SOEC and AEM are in the development phase and may provide better performance in the future. (IRENA 2021.)

Figure 2 below helps to outline the value chain of green hydrogen. Renewable energy production refers to electricity produced by wind or solar power, which acts as energy input for electrolysis. In electrolysis, water is broken down into hydrogen and oxygen. In storage and pressurization, hydrogen is stored either as a compressed gas, liquefied or possibly in chemical form, such as ammonia. Hydrogen is transferred from the place of production to the place of use by pipelines, tanks, trucks or ships. Green hydrogen can be used in industrial sectors such as steel production, in transport or as energy storage to balance the electricity grid, for example, to maintain balance between supply and consumption of electricity. (IRENA 2021.)

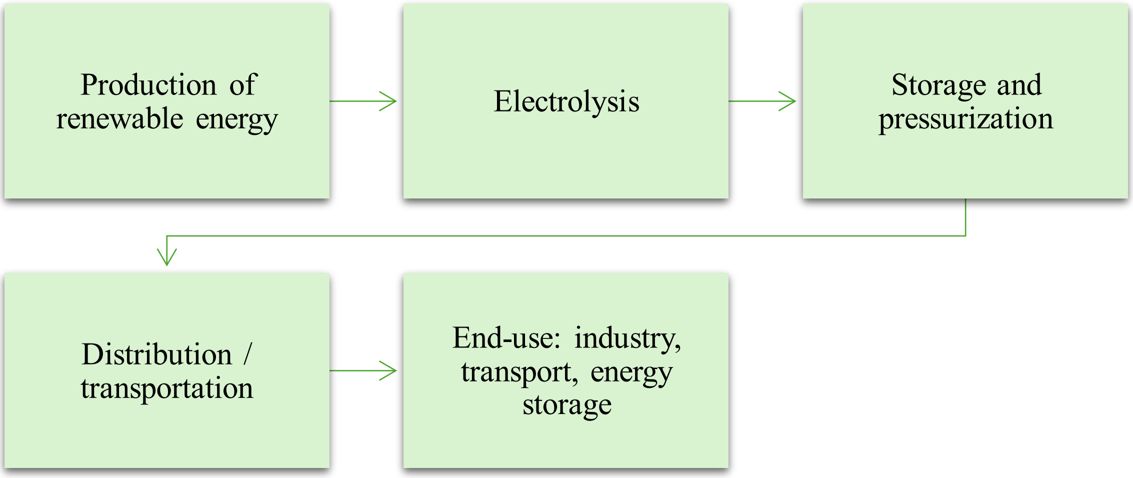

Figure 2. Green hydrogen value chain. (Modified from IRENA 2021).

2.2 Role in the energy transition and climate targets

A sustainable energy transition refers to a wide-ranging change in the production, distribution and consumption of energy. The goal of the energy transition is to shift away from fossil fuels towards a system that relies on renewable energy sources. In order to solve the climate crisis, this transition is very important, and green hydrogen is often seen as a key solution for meeting climate goals and achieving sustainable energy transition. (UNP 2025.) The role of green hydrogen in achieving climate goals is based not only on zero emissions, but also on the ability to provide flexibility, storage opportunities and cross-sectoral connectivity in the energy system (Lintunen 2023). The EU has high climate targets, but Europe is also heavily dependent on fossil fuel imports. Hydrogen can help reduce the need for imported energy, improve security of supply, and decentralize energy production. (European Parliament 2025.)

Green hydrogen complements renewable energy by enabling the storage of renewable electricity. Hydrogen can be stored either in a pressurized tank or in underground geological formations. Tank storage takes place under high pressure and is most used in industry in situations where small storage volumes of up to 10 000 m^3 and frequent use are required. Underground storage, on the other hand, allows long-term storage of large amounts of hydrogen at lower pressures. Although hydrogen storage technologies are suitable for all types of hydrogen, regardless of how it is produced, the role of storage is particularly emphasized in the production of green hydrogen. As green hydrogen production is often weather-dependent due to wind and solar variability, storage enables its use even when electricity generation is low and thereby supports the balance of the entire energy system. (IRENA 2021.)

Hydrogen plays an important role not only in increasing the flexibility of energy production, but also in connecting different industrial and energy sectors. This sector coupling means combining different energy sectors, such as electricity production, heating, transport and industry, into a functional and flexible entity. The aim is to make the most efficient use of common infrastructure and energy flows. Hydrogen plays a key role in this, as it can be used to turn electricity into gas and other end products that can be used in sectors where direct electrification is not technically or economically feasible. For example, green hydrogen makes it possible to utilize surplus electricity production in industry, transport or heating.

Hydrogen can be used to combine previously separated sectors, such as the electricity and fuel markets, the chemical industry and metal processing. This enables the construction of a completely new, emission-free energy system in which different energy sectors work well together. For example, ammonia, which has traditionally been used as fertilizer, may also be used in electricity production or as fuel for ships in the future. It can also act as a hydrogen-based energy carrier that allows clean energy to be transported and stored globally in molecular form. (Hydrogen Council 2021.)

The role of green hydrogen within the broader energy transition framework is summarized in figure 3. Green hydrogen can support renewable energy integration, enhance energy security, enable energy storage, and promote sector coupling across industry and transport.

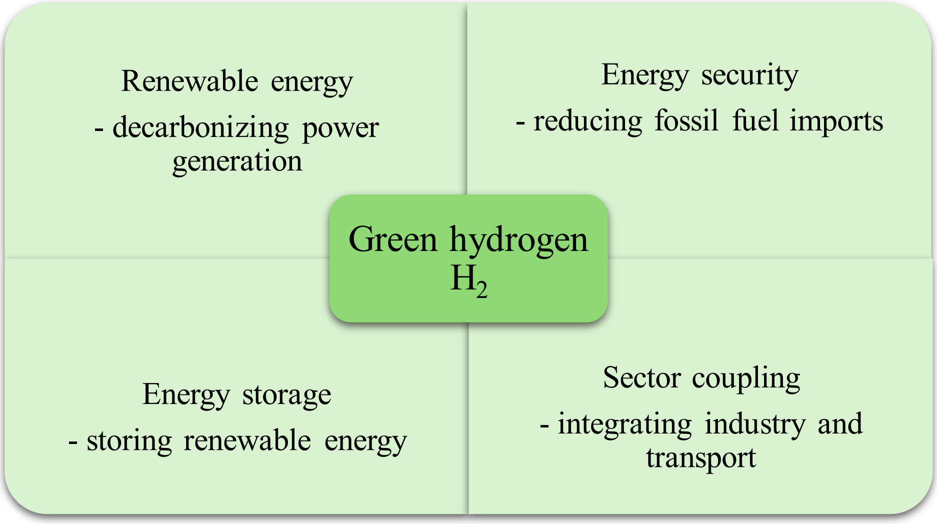

Figure 3. The role of green hydrogen across different sectors.

3 Hydrogen strategy and policy in Europe

After Russia's war of aggression, the importance of Europe's energy self-sufficiency was emphasized and the role of renewable hydrogen increased. The war accelerated the EU’s efforts to reduce its dependence on Russian energy, which increased Europe's need to transition to more self-sufficient and sustainable energy production. The role of renewable hydrogen was emphasized more as part of the strengthening of the European energy system. (European Commission 2024.)

In response to the energy market disruptions, the European Commission published the REPowerEU plan, which aims to reduce dependence on Russian fossil energy. As part of this plan, the Hydrogen Accelerator was launched, doubling the EU's previous targets for renewable hydrogen production. The goal is that by 2030, the EU will produce 10 Mt of renewable hydrogen and import the corresponding amount of hydrogen outside the EU. (European Commission 2024.)

Renewable hydrogen also plays a key role in the European Green Deal, which aims to make Europe climate-neutral by 2050. The European Green Deal emphasizes the hydrogen economy, especially in sectors where direct electrification is not technically or economically feasible. In 2020, the European Commission published a separate hydrogen strategy, which sets out policy actions in five key areas:

1. Building a hydrogen market and infrastructure
2. Research and innovation
3. Regulatory framework
4. Balancing supply and demand
5. International cooperation

To support the strategy, the European Clean Hydrogen Alliance was established, which brings together industry, government and research actors to promote the hydrogen economy. The Commission estimates that investments in renewable hydrogen in the EU could reach between 180 billion and 470 billion euros by 2050. (European Commission 2024.)

EU is globally a key player in the development of the hydrogen economy. The EU's 27 Member States form the world's third largest economic area, and the climate targets of the EU strongly guide the deployment of renewable hydrogen. Energy and climate policy is developed in cooperation between the Member States, but the regulatory framework and common goals are largely shaped by the European Commission and the European Parliament. (European Union n.d.)

The EU has clearly defined strategic objectives for the development of the hydrogen economy. It has published a hydrogen roadmap and launched extensive policy and funding programmes such as REPowerEU, Fit-for-55, the Clean Hydrogen Partnership, IPCEI projects and the European Hydrogen Bank. These initiatives aim to accelerate the development of the hydrogen economy. In addition to the programmes, the EU's internal market and common legislation allow the hydrogen economy to be analyzed as a coherent entity across different countries. (European Partnership 2024.) The goal of the EU is to significantly increase the production of renewable hydrogen by 2030 and to promote its use, especially in industry and heavy-duty transport. At the same time, the aim is to reduce dependence on imported fossil energy sources, particularly natural gas. (European Parliament 2025.)

3.1 EU regulatory framework for green hydrogen

This chapter examines the key pieces of legislation on the production and use of green hydrogen and the related emission and sustainability criteria at the EU level. The legislation and sustainability criteria ensure that green hydrogen genuinely supports the climate and energy targets in the EU.

3.1.1 Legislation related to green hydrogen utilization

The EU is committed to achieving climate neutrality by 2050, and in 2021, the legislation set a mid-term target of reducing greenhouse gas emissions by 55% by 2030 compared to 1990 levels. This milestone requires emission reductions, particularly in transport, energy production and industry, which accounted for the majority of the EU’s emissions in 2020. (European Court of Auditors 2024.)

In recent years, hydrogen legislation at the EU level has become significantly more precise, especially regarding the production and utilization of renewable hydrogen. A key guiding document is the third version of the Renewable Energy Directive, RED III, which sets binding targets for the use of renewable hydrogen and other renewable fuels, especially in industry and transport. RED III serves as a legal basis for several legislative instruments supporting the development of the hydrogen economy. (European Hydrogen Observatory 2025b.)

In February 2023, the European Commission published two key delegated acts that define the conditions under which hydrogen produced by electrolysis can be classified as renewable. Among other things, the regulations address the principle of additionality, the original requirements for renewable electricity, and clarify how GHG emissions of renewable hydrogen are calculated in a situation where hydrogen is produced in a plant producing fossil-based fuels. The aim is to ensure that renewable hydrogen genuinely supports climate goals and does not put extra pressure on the electricity system. (European Commission 2023a)

In 2024, the EU adopted the comprehensive Hydrogen and Gas Decarbonisation Package, which consists of Directive EU 2024/1788 and Regulation EU 2024/1789. This Gas Package updates the old natural gas regulations and introduces an entirely new regulatory framework for hydrogen infrastructure. It will create the conditions for an intra-EU hydrogen market, facilitate the development of a cross-border hydrogen network and enable the conversion of existing natural gas infrastructure for hydrogen use. (European Commission n.d.)

In addition, several other legislative measures support the development of the hydrogen economy as part of the wider energy transition. The ReFuelEU Aviation Regulation aims to reduce emissions from aviation fuels by increasing the share of synthetic fuels produced from renewable sources, such as hydrogen, to 70% by 2050. The FuelEU Maritime Regulation, on the other hand, aims to reduce the carbon footprint of maritime energy by 80% by 2050 by utilizing hydrogen-based fuels. The TEN-E Regulation covers the cross-border development of energy infrastructure and supports the expansion of the hydrogen economy throughout the EU. The Net Zero Industry Act aims to promote investments in green technologies and facilitate the commercial deployment of hydrogen-related solutions in Europe. (European Court of Auditors 2024.)

3.1.2 EU emission criteria for sustainable hydrogen

The EU taxonomy for sustainable finance defines the technical criteria for when an economic activity can be considered environmentally sustainable. For hydrogen, these criteria were defined in a delegated act adopted by the European Commission in April 2021. The act is part of the EU's financial framework for climate policy and the green transition, and its purpose is to steer investments towards activities that support emission reduction targets. (Sivill et al. 2022)

To be considered sustainable under the taxonomy, hydrogen production must meet several conditions. Life cycle greenhouse gas emissions must be at least 73.4 % lower compared to fossil benchmarks. In practice, this means that the lifecycle emissions from hydrogen production may not exceed 3 t $CO_{2,eq}$ / t H_2 produced. For synthetic hydrogen fuels, the required emission reduction is 70 %, using a fossil fuel reference value which is 94

$gCO_{2,eq}$/MJ. Emission calculations must be based on methods in accordance with the ISO 14067:2018 or ISO 14064-1:2018 standards. (Sivill et al. 2022)

In addition, economic activities related to hydrogen production are required to take climate risks into account. This means that production must be based on solutions that significantly reduce climate risks. Operators are required to carry out a risk and vulnerability analysis, for example using the methods recommended by the IPCC, and to ensure that any adaptation measures do not cause harm to other sectors or regions. The aim of these requirements is to ensure that investments in hydrogen support the EU's climate objectives and genuinely contribute to the transition towards a low-carbon economy. (Sivill et al. 2022.)

3.2 Strategies of the EU Member States

Although the EU has created an ambitious strategic framework to promote the hydrogen economy, implementation and priorities vary between the Member States. The regulatory measures, production subsidies and demand quotas introduced at the EU level form a coherent vision, but their implementation largely depends on national resources and political will. One of the challenges is the disagreement between Member States on issues such as the definition of renewable hydrogen, the allocation of funding and the development of infrastructure. These challenges have led to divergent progress in the implementation of hydrogen policy between EU countries. (Quitzow, Zabanova 2024.)

This chapter provides brief outlines of the hydrogen strategies of selected EU Member States, illustrating their approaches to developing the hydrogen economy. For clarity, the selected countries are presented in geographically grouped sections. The chapter also provides a background on the selected front-runner countries, Germany, Spain, the Netherlands and Sweden, which are discussed in more detail in chapter 5. These countries have the highest green hydrogen production targets and the most concrete progress towards large-scale deployment.

Germany, the Netherlands and France are among the largest hydrogen economies in Continental Europe. Germany's hydrogen strategy aims to support carbon neutrality in industry by 2045 and strengthen the country's position as a technology leader in the hydrogen economy. The strategy emphasizes international partnerships, hydrogen imports and the use of green hydrogen in emission-intensive sectors, such as the steel and chemical industries. Germany will also allow limited use of blue hydrogen during the transition period. (Nunez, Quitzow 2024.) The Netherlands' hydrogen strategy is based on the country's strong position in the energy sector and ambitious climate targets. The country is focusing its hydrogen strategy on energy and port infrastructure as well as import logistics. It aims to become a hub for hydrogen production, import and distribution in Europe. The Netherlands will also accept the use of blue hydrogen through CCS technology in transition. (Stam et al. 2024.) The focus of France's hydrogen strategy is particularly on reducing emissions from industry and heavy-duty transport. The strategy emphasizes low-carbon hydrogen produced using both renewable and nuclear power. France aims to build a domestic hydrogen economy and technological development, but the large-scale production targets for green hydrogen are moderate for the time being. France has also actively sought to have nuclear-produced hydrogen included in the EU's sustainability criteria. (Bouacida 2024.)

Italy and Spain represent Southern European approaches to the development and deployment of hydrogen systems. In Italy, the development of the hydrogen economy is largely linked to EU recovery funding and Hydrogen Valley projects (Prontera 2024). Although Italy sees green hydrogen as a potential solution for emission reductions, especially in industry and transport, the country's strategic production targets are still under development (Sivill et al. 2022). Spain's hydrogen strategy relies heavily on renewable electricity and is export-oriented. The country has a strong commitment to renewable hydrogen as part of its industrial renewal and economic restructuring, and this is reflected in its ambitious electrolysis capacity targets. A central element of Spain's hydrogen strategy is the closer integration of the Iberian Peninsula into the EU hydrogen market through cross-border infrastructure. (Urbasos, Escribano 2024.)

Sweden, Denmark and Finland represent Northern European hydrogen strategies. Sweden's hydrogen strategy currently focuses entirely on domestic production and use. The country relies heavily on a fossil-free electricity system and an industry-driven approach in which green hydrogen is utilized especially in the renewal of emission-intensive industrial processes, such as the steel industry. (Cetkovic, Stockburger 2024.) Denmark's hydrogen strategy focuses primarily on green hydrogen and Power-to-X technologies, supported by its strong offshore wind potential. The country emphasizes decarbonizing shipping, aviation and heavy transport, and aims to become an exporter of hydrogen-based fuels and technologies to European markets through investments in infrastructure and storage solutions. (Green Hydrogen Organisation 2026.) Finland aims to strengthen its long-term position in the hydrogen economy, especially on the basis of renewable electricity and industrial expertise. Although the plans are ambitious, many projects are still in the early stages of development. (Finnish Government 2023.)

3.3 EU support mechanisms and investment programmes

The development of the hydrogen economy in Europe requires significant investments in infrastructure, production technologies and research. According to the European Commission, the production, transmission and use chain of 10 Mt of renewable hydrogen would require a total investment of up to 470 billion euros. At least half of this sum will be allocated to the construction of additional renewable electricity production. (European Commission 2023b). As not all Member States can make the necessary investments on their own, the EU has created various funding mechanisms to support the construction and scaling up of the hydrogen economy. These tools will encourage both private and public actors to invest in hydrogen-related projects and technologies. (European Commission n.d.) Key investment programmes include the Innovation Fund, InvestEU, the Connecting Europe Facility (CEF) and Horizon Europe, which support research, infrastructure and the deployment of technologies across Europe. (Penttinen 2024.)

The Innovation Fund will finance low-carbon technologies and pilot plants, while InvestEU will provide financial guarantees for high-risk projects and aim to attract private investors to hydrogen economy projects. CEF supports cross-border energy and transmission infrastructure, such as the H2Med and AquaDuctus projects, which aim to build a hydrogen economy transport network within Europe. In addition, Horizon Europe focuses on research and development projects, many of which are related to Hydrogen Valley pilot areas and new hydrogen solutions. (Penttinen 2024.)

Together, these funding programmes will lay the foundations for the growth of the EU's hydrogen economy. They aim to strengthen investment certainty, accelerate the scale-up of green hydrogen production and support the transition towards a market-based and competitive hydrogen economy across Europe. (Penttinen 2024.) The following sections examine the main EU level support mechanisms in more detail.

3.3.1 European Hydrogen Bank

As part of building a market for green hydrogen, the EU established the European Hydrogen Bank, which aims to support the production of renewable hydrogen, increase the visibility of demand and close the cost gap between renewable and fossil hydrogen. The Bank consists of four pillars: two financing mechanisms, data coordination to increase the transparency of supply and demand, and coordination of financial instruments at EU level. (European Commission 2023b)

One of the bank's most important means is an EU level auction, in which renewable hydrogen producers are paid a fixed premium for the hydrogen produced. The first pilot auction was held in 2023 with a budget of 800 million euros. The aim is to enable the formation of market prices and to promote the financing of hydrogen production projects. In the future, Member States will be able to use the EU's auction platform with their own resources to complement EU funding. (European Commission 2023b.)

Together with external actors, the Bank supports hydrogen imports from outside the EU and aims to ensure the sustainability of hydrogen production and the management of geopolitical and resource risks. The goal is to bring 10 Mt of renewable hydrogen to the EU by 2030. (European Commission 2023b)

3.3.2 IPCEI projects

The Important Projects of Common European Interest (IPCEI) is the strategic funding mechanism that supports research, innovation and first-stage industrial deployment within the EU. IPCEI projects require European added value and participation by at least four Member States. In 2022, two hydrogen-focused IPCEI projects were approved:

1. H2Tech: 5.4 billion euros in public support, involving 35 companies, 41 projects, and 15 Member States
2. H2Use: 5.2 billion euros in public support, involving 29 companies, 35 projects, and 13 Member States

In total, these projects are expected to mobilize up to 15.8 billion euros of private investment. Although IPCEI projects cover the entire hydrogen value chain, from production to use, its acquisition is a complex and time-consuming process. In addition, there are often delays in the introduction of funding, which has caused criticism especially from the perspective of small and medium-sized enterprises. Despite this, IPCEI projects are currently one of the key tools in the EU for developing the hydrogen economy and promoting cooperation between Member States. (Zabanova 2023.)

3.3.3 Hydrogen Valleys

The Hydrogen Valley concept refers to a geographically limited area that connects the entire hydrogen value chain from production to storage, transport and end-use. Hydrogen Valleys are supported by the EU through various programmes such as the Clean Hydrogen Partnership. (Clean Hydrogen Partnership n.d.) Hydrogen Valley projects are characterized by their large size and multi-source financing, consisting of private and public investments. The annual production capacity varies from hundreds of tonnes to several thousand tonnes, and the aim of the projects is to create regional clusters where different actors benefit from common infrastructure and cooperation. The benefits of the concept include cost-effectiveness through economies of scale, shared use of infrastructure, the creation of new jobs and the opportunity to test regulatory solutions in practice. (Bampaou, Panopoulos 2025.)

In 2025, there were approximately 90 Hydrogen Valley projects underway in the world, most of which are located in Europe. Electrolysis is mainly utilized in production, storage is usually carried out as compressed gas and transport by pipelines or trucks. In this way, the Hydrogen Valley projects build the foundation for a large-scale hydrogen economy and support Europe's climate targets and energy self-sufficiency. (Bampaou, Panopoulos 2025.)

3.3.4 European Hydrogen Backbone

The European Hydrogen Backbone (EHB) is a joint initiative of the transmission system operators of the European gas and hydrogen networks, which aims to enable the large-scale production, transmission and use of renewable and low-carbon hydrogen in Europe. The project involves 33 actors and covers almost the entire existing gas transmission network in the EU. EHB is largely based on the conversion of the existing natural gas network to hydrogen, which reduces the need for investment and supports a faster deployment of the hydrogen economy. (EHB 2025.) The EHB initiative aims to build a 58 000 km hydrogen pipeline network by 2040 and will connect approximately 28 European countries (GIE 2024). The EHB is designed to connect large industrial hydrogen consumers to regions that offer strong renewable energy production potential. Priority development is therefore concentrated at the North Sea, Central Europe and the Mediterranean regions. (Jens et al. 2021.)

4 Methodology

This chapter describes the research approach, data selection, limitations and calculation formulas used in this master’s thesis. The thesis aims to provide an overall picture of the current state of green hydrogen, the policy framework, and its emission reduction potential and prospects in Europe. The work draws on current EU policy documents, regulations, reports and studies by experts in the field. The review focuses on the EU, as it plays a key role in promoting the hydrogen economy at the global level. In addition, four front-runner countries have been selected for more detailed analysis.

4.1 Research approach and data selection

This master's thesis is conducted as a qualitative study in the form of a literature review. The thesis examines the development of the hydrogen economy in Europe and related opportunities and challenges. The study does not include empirical data collection but is based on existing literature and official data. The material in the literature review consists of recent and reliable sources that are central to the hydrogen economy in the EU. The sources used are official documents of the European Commission and the European Parliament, publications of energy research institutes, reports of international organizations such as IEA and Hydrogen Europe, and scientific literature on the subject. When selecting the data, attention has been paid to timeliness, reliability and the suitability in forming an overall picture of the EU hydrogen strategy.

The thesis also includes a scenario-based calculation of the electricity demand, production volumes and emission reductions if grey hydrogen production is replaced with green hydrogen production in selected front-runner countries. Scenario-level, order-of-magnitude estimates are used in the calculations, meaning that the results are indicative rather than accurate forecasts.

4.2 Case area: Front-runner countries

The case area is limited to four front-runner countries in green hydrogen development: Germany, Spain, the Netherlands and Sweden. The countries were selected based on their ambitious electrolysis capacity targets, investment activity and strategic importance at the EU level. Their national hydrogen strategies are examined in more detail, and the collected information is used to analyze country-level estimates of the electricity demand required for meeting their own electrolysis capacity targets, the corresponding hydrogen production volumes, and the emission reduction potential if grey hydrogen is replaced by green hydrogen.

The countries were selected to provide concrete examples of how green hydrogen development may differ across national contexts. For example, some countries, such as Denmark, currently have relatively high installed capacity, but their planned electrolysis capacity deployments toward 2030 are smaller than those of the selected front-runner countries. Therefore, the selection focuses on countries with the largest capacity growth and expected future impact.

4.3 Calculation framework and assumptions

The calculations focus on Germany, Spain, the Netherlands and Sweden based on their electrolysis capacity targets set for 2030, which are presented in more detail in section 5.1. The calculation framework is in line with the EU's Renewable Energy Directive and the sustainable finance taxonomy mentioned in section 3.1.2. According to the regulations, hydrogen is considered sustainable if its production life cycle emissions do not exceed 3 t $CO_{2,eq}$ / t H_2. The production of green hydrogen examined in this thesis is based on the use of renewable electricity and therefore meets the EU sustainability criteria. Because small life cycle emissions arise due to manufacturing electrolysers, renewable electricity infrastructure and supply-chain processes, green hydrogen is not considered fully zero-carbon. These emissions are assumed to be 0.5-1 kg $CO_{2,eq}$ / kg H_2 in the calculations. (MIT Climate 2024.)

Grey hydrogen is used as a benchmark for assessing emission reductions, as it is currently the most common form of hydrogen production in Europe. Its average life cycle emissions are 9.3 kg $CO_{2,eq}$ / kg H_2. (Erbach, Jensen 2021.) However, higher values of around 11-13.7 kg $CO_{2,eq}$ / kg H_2 are reported when upstream natural gas supply emissions are included (Moberg, Bartlett 2022). This variability is reflected by applying a range of emission factors in the calculations.

Renewable electricity production varies according to weather conditions, which also affects the capacity factor of electrolysers. In this study, the capacity factor is assumed to be 35%. This assumption represents an average based on the typical capacity factors of solar PV (12-35%), onshore wind (15-53%) and offshore wind (32-67%) in Europe. (IEA 2024.)

These assumptions are based on published estimates by the EU and the IEA, as well as typical values of green hydrogen production technologies, specifically PEM and alkaline electrolysis. The analysis focuses on targets set for the 2030–2050 period. The assumptions used in the calculations are presented in table 2 below.

Table 2. Assumption used in the calculations.

Assumption	Value/scope	Explanation
Electricity consumption in electrolysis	approx. 50 kWh / kg H_2 (IEA 2024b)	Average energy demand for hydrogen production using renewable electricity
Emission factor range for green hydrogen	0.5-1.0 kg $CO_{2,eq}$ / kg H_2 (MIT Climate 2024)	Life-cycle emissions for electrolysis with renewable electricity
Emission factor range of grey hydrogen	9.3-13.7 kg $CO_{2,eq}$ / kg H_2 (Erbach, Jensen 2021; Moberg, Bartlett 2022)	Used as a reference value in emission reduction calculations
Assessment period	2030-2050	Corresponds to EU's intermediate climate targets
Capacity factor of electrolysers (CF)	35 % (IEA 2024)	Used for order-of-magnitude estimates of electricity demand for hydrogen production

These assumptions presented in table 2 form the basis for the following equations used to estimate electricity demand, hydrogen output and the associated emission reductions when replacing grey hydrogen with green hydrogen. Emission factor ranges are used to define lower and upper bounds for the emission reduction in front-runner countries. The minimum emission reduction is calculated by using the lowest emission factor for grey hydrogen and the highest emission factor green hydrogen. The maximum reduction is calculated by using the highest emission factor for grey hydrogen and the lowest emission factor for green hydrogen.

Annual electricity demand for electrolysis capacity target is calculated using equation 1:

$$E_{electricity} = P_{capacity} \times 8760\ h \times CF \qquad (1)$$

where $E_{electricity}$ in the annual electricity demand (kWh/year), $P_{capacity}$ is the total power of electrolysers (kW), *8760* is the number of hours per year, and *CF* is the capacity factor.

The annual hydrogen production volume is calculated using equation 2:

$$m_{H_2} = \frac{E_{electricity}}{e_{electrolysis}} \qquad (2)$$

where $m_{H_2}$is the mass of hydrogen produced (kg/year) and $e_{electrolysis}$ is the electricity demand per kilogram of hydrogen produced (kWh/kg H_2).

Grey hydrogen emissions are calculated using equation 3:

$$CO_{2grey} = m_{H2} \times f_{grey} \qquad (3)$$

where CO_{2grey} represents the annual emissions from grey hydrogen production (kg $CO_{2,eq}$ / year), m_{H2} is the produced hydrogen mass (kg/year) and f_{grey} is the emission factor of grey hydrogen (kg $CO_{2,eq}$ / kg H_2).

Green hydrogen emissions are calculated using equation 4:

$$CO_{2green} = m_{H2} \times f_{green} \qquad (4)$$

where $CO_{2_{green}}$ is the annual emissions from green hydrogen production (kg $CO_{2,eq}$ / year), m_{H_2} is the produced hydrogen mass (kg/year) and f_{green} is the emission factor of green hydrogen (kg $CO_{2,eq}$ / kg H_2).

The emission reduction replacing grey hydrogen production with green hydrogen is calculated using equation 5:

$$CO_{2_{reduction}} = m_{H_2} \times (f_{grey} - f_{green}) \tag{5}$$

where m_{H_2} is the produced hydrogen mass (kg/year), f_{grey} is the emission factor for grey hydrogen and f_{green} is the emission factor for green hydrogen.

It should be noted that the calculated emission reductions represent a theoretical substitution effect. The calculations assume that green hydrogen replaces grey hydrogen production within the EU hydrogen market and do not necessarily correspond to direct national emission reductions in the analyzed front-runner countries.

5 Results

The production of green hydrogen in Europe has progressed faster than in the rest of the world, as the EU's strict climate policy and financial instruments for the green transition have increased investments, especially in electrolyser technologies and hydrogen economy infrastructure (European Commission 2025). The European Commission's goal of producing 10 Mt of renewable hydrogen by 2030 requires a significant amount of electricity, as the electrolysis process requires about 50 kWh / kg H_2. This means that achieving the 10 Mt hydrogen target would require approximately 500 TWh of electricity. The high electricity demand highlights the need for additional renewable energy production to produce green hydrogen.

Previous chapters have presented the background to hydrogen production, the strategic objectives of the EU and the different approaches of the Member States to develop the hydrogen economy. This chapter focuses on the results of the study, examining the current state and prospects of green hydrogen production in the EU and in selected front-runner countries. The results are based on data from the literature review and a computational estimate of the electricity demand of the electrolysis capacity targets and the related emission reduction potential if grey hydrogen production is replaced by green hydrogen production. The aim of this chapter is to highlight the key opportunities and challenges of green hydrogen at the EU level and to provide an overall picture of the role that it can play in front-runner countries as part of wider energy transition in the EU.

5.1 Hydrogen opportunities in different sectors in Europe

In industry, green hydrogen is emerging as one of the most important applications in Europe. Especially in the chemical industry, oil refining and ammonia production, the processes are mostly based on hydrogen made from natural gas. Replacing fossil-based hydrogen with green hydrogen could reduce an estimated 60 Mt of CO_2 emissions annually at the EU level. In addition, hydrogen enables the production of high-temperature process heat and acts as a reducing agent in the steel industry, where its use could cover 20% of production by 2050. (Reigstad 2025.) For example, Germany and Sweden have integrated green hydrogen into their industrial decarbonization strategies, particularly in steel and chemical industries as outlined in section 3.2.

In the transport sector, the use of hydrogen is considered particularly promising, especially in heavy-duty road transport and rail transport. Heavy vehicles accounted for about 27% of road transport emissions in 2022 (Destatis 2023). Replacing fossil fuels with hydrogen in heavy-duty transport could result in annual emission reductions of up to 271 Mt by 2050. Hydrogen-powered trains can also replace diesel locomotives in rail transport, especially in areas where rail electrification is not available. (Reigstad 2025.)

In electricity generation, hydrogen can be used to replace natural gas, especially in peak and reserve power plants. The advantage of hydrogen is its ability to support the flexibility of the electricity grid without CO_2 emissions, unlike natural gas without carbon capture. It is estimated that hydrogen could cover around 180 TWh of electricity generation by 2050, corresponding to an annual emission reduction of approximately 29 Mt CO_2. (Reigstad 2025.)

The key role of green hydrogen in Europe is particularly focused on sectors where direct electrification is technically or economically challenging. The best opportunities for green hydrogen in Europe are primarily linked to sectors where emission reductions through other means are limited. Green hydrogen is seen as a complementary solution to electrification, and its role is emphasized in industrial processes, heavy-duty transport and in supporting energy system flexibility. Table 3 below gathers the key opportunities for the use of green hydrogen in the sectors described above.

Table 3. Key opportunities of green hydrogen across different sectors in EU.

Sector	Key opportunities
Industry	Fossil hydrogen replacement High temperature heat Green steel production
Transport	Emission reduction in heavy-duty transport Hydrogen use in non-electrified rail E-fuels for shipping and aviation
Power System	Energy storage Grid balancing Backup power

5.2 Economic, technical and political challenges of hydrogen

Although the production of green hydrogen has significant emission reduction potential, its large-scale deployment faces several economic, technical and policy-related challenges. These challenges are not uniform across EU Member States, but they are linked to each country's energy system, industrial structure and policy frameworks. The high production cost of green hydrogen is one of the key challenges in all EU countries examined. The production cost of green hydrogen is currently about two or three times higher than fossil-based hydrogen. In 2023, the average production costs of electrolysis-based hydrogen were around 7.9€/kg and ranged from 4€ to 17€/kg. High costs discourage investments and increase the financial risk of projects, highlighting the importance of public support mechanisms. (Corbeau, Nassif 2025.)

Technical challenges are mainly related to insufficient infrastructure and the availability of renewable electricity. In several EU Member States, limited grid capacity, slow permitting processes and delays in connecting electrolysers to the grid constrain the rapid growth of hydrogen production. In addition, the logistics of the hydrogen economy, such as transmission networks and import terminals, are still at an early stage of development in many countries. This makes it more difficult for industrial users to access hydrogen. The regional imbalance between production and demand highlights the need to develop cross-border infrastructure. (Corbeau, Nassif 2025.)

Political and regulatory challenges represent a major source of uncertainty. Delays in regulation related to the definition of renewable hydrogen have slowed down investment decisions, and differences in national strategies and support practices have led to fragmentation of the internal market. In addition, funding for IPCEI projects is highly concentrated in a few large EU Member States, which can undermine balanced development across the EU. Bureaucratic permitting processes and regulatory complexity increase the risks of projects and may lead to industrial investments relocating outside the EU. (Corbeau, Nassif 2025.) For example, the strategies of France to promote hydrogen produced using nuclear power or CCS technology illustrate differences within the EU framework.

In summary, the potential of green hydrogen to contribute to climate goals is significant, but its realization requires coordinated policies at the EU level, long-term investments and the systematic removal of economic and technical barriers. Without these measures, the role of green hydrogen in achieving the 2030 emission reduction targets is likely to remain limited. Table 4 below summarizes the key challenges related to the large-scale deployment of green hydrogen in Europe.

Table 4. Key barriers of green hydrogen across different sectors in EU.

Barrier type	Key barriers
Technical	Lack of infrastructure Insufficient renewable electricity Slow permitting and grid connections
Economic	High production costs Low investor interest Weak willingness to pay without support mechanisms
Political	Complex and delayed regulation Fragmented national policies Unequal funding distribution

5.3 National development in front-runner countries

The following front-runner country cases illustrate how the EU level opportunities and challenges translate into national strategies, capacity targets and concrete hydrogen projects in practice. The selected countries have progressed the furthest in green hydrogen development in the EU and represent some of the most advanced examples in the area.

5.3.1 Germany

Germany is one of the key players in the European hydrogen economy, and it has increased its electrolysis capacity target from 5 GW to 10 GW by 2030 in an update of its hydrogen strategy. This target would require approximately 1000 green hydrogen plants with a capacity of 10 MW each. However, in 2022, Germany’s installed green hydrogen capacity was only 57 MW. Hydrogen production in Germany in 2022 totalled 1.71 Mt, of which green hydrogen accounted for only 5 % through electrolysis processes. These figures show that the 10 GW target over the next four years will require a significant acceleration in annual deployment. (Buchner et al. 2025.)

Several EU level programmes have been introduced to support the development of the German hydrogen market, most importantly the IPCEI projects and the H2Global programme. With the help of IPCEI funding, Germany aims to build more than 1800 kilometers of new and modified hydrogen pipelines and a further 4500 kilometers across Europe as part of the European Hydrogen Backbone network in 2027–2028. These investments are intended to lay the foundations for a national hydrogen backbone network, with a total estimated length of around 10 000 kilometers. This network will connect production, storage, imports, and major industrial hubs by 2032. (The Federal Government 2024.)

Imports play a key role in ensuring the availability of green hydrogen in Germany. Germany's estimated demand by 2030 is 95-130 TWh, of which around 50-70 % is expected to be imported from abroad either as green hydrogen or in the form of derivates. Most of the upcoming supply contracts are still at the negotiation phase, but Germany has launched more than 30 bilateral energy and climate partnerships to promote green hydrogen imports. (The Federal Government 2024.) At the same time, budget cuts and uncertainty regarding the role of blue hydrogen have emerged as challenges in Germany’s hydrogen strategy. (Nunez, Quitzow 2024).

5.3.2 Spain

Spain is one of Europe's most promising producers of green hydrogen, as the country benefits from its solar and wind resources, as well as well-developed industrial infrastructure. Spain aims to achieve 12 GW of electrolysis capacity by 2030, compared to the previous target of only 4 GW. However, in 2024, there was only about 50 MW of electrolysis capacity in operation, meaning that rapid growth is required to achieve the target. Despite this, several industrial-scale projects, such as Iberdrola’s 20 MW plant in Puertollano and Repsol’s demonstration plants, have been commissioned. In addition, green hydrogen production plants with a combined electrolysis capacity of at least 1 GW are under construction for the period 2025–2027. (Cáceres 2025.)

A crucial project for hydrogen infrastructure is the H2Med pipeline. This 3000-kilometer network is planned to be commissioned by 2030 and will enable the export of green hydrogen to countries such as Germany and France. Spain's hydrogen economy has moved from the planning phase to implementation, and if the planned investments and interconnections are completed on schedule, Spain has a realistic chance of reaching its 12 GW electrolysis capacity target. (Cáceres 2025.)

In Spain, the green hydrogen targets are supported by several national and EU level funding mechanisms aimed at supporting the expansion of the hydrogen economy and investments in renewable energy. EU level support mechanisms that Spain uses include the Innovation Fund, the Connecting Europe Facility (CEF), the InvestEU Fund and the European Hydrogen Bank. These instruments support the transition to a low-carbon economy and the development of renewable hydrogen infrastructure, helping Spain to build a competitive green hydrogen value chain. (MITERD 2020.)

5.3.3 The Netherlands

The Netherlands is well positioned to produce green hydrogen, as the country can benefit from the extensive offshore wind power potential of the North Sea and its well-developed port infrastructure. The Netherlands has set a target of achieving 3-4 GW of electrolysis capacity by 2030, while more ambitious scenarios indicate a potential capacity of 6-8 GW by 2030. (IEA 2025b) In 2021, the electrolysis capacity in the Netherlands was only around 3 MW (Green Hydrogen Organisation n.d.). Despite this, several industrial-scale green hydrogen projects are under construction, including Holland Hydrogen I (200 MW), OranjeWind (795 MW) and NortH2. These projects are expected to increase the production capacity in the Netherlands between 2025 and 2030. (IEA 2025.)

The Dutch government is aiming for 21 GW of offshore wind power capacity by 2032 and with a longer-term target of up to 70 GW by 2050. A large share of this electricity is planned to be used directly in electrolysers for hydrogen production, enabling more efficient use of renewable energy. Also, an extensive hydrogen infrastructure is being developed in the Netherlands, with plans to connect it to the European Hydrogen Backbone network at the beginning of 2030. (IEA 2025b.)

In addition, The Netherlands is actively pursuing hydrogen production based on carbon capture and storage (CCS), which is intended to complement the production of green hydrogen. If all planned electrolysis and CCS projects are completed within the planned timeframe, the country could produce more than 1.5 Mt of low-emission hydrogen by 2030. This amount would be enough to cover almost all of the Netherlands' current hydrogen consumption. (IEA 2025b.)

The development of green hydrogen is supported by both national and EU level funding programmes. The Dutch Government has reserved nearly 8 billion euros for hydrogen development for the period 2023–2030, most of which is intended for electrolysis capacity based on offshore wind power. Key support mechanisms include the OWE programme, which provides investment and operational support for electrolysers, and SDE++, which grants production support to produce low-emission hydrogen. In addition, the Netherlands participates in the H2Global cooperation with Germany and is also involved in several EU IPCEI Hydrogen projects that promote the construction of a hydrogen economy value chain. (IEA 2025b.)

5.3.4 Sweden

Sweden has made progress in the development of green hydrogen, especially in terms of emission reductions in industry, and the country benefits from almost fossil-free electricity system in hydrogen production. Sweden's goal is to expand its electrolysis capacity to 5 GW by 2030, and by 2045 the capacity is expected to be around 50% higher. However, the development of the hydrogen economy is still slowed by shortcomings in national coordination and the lack of a clearly defined hydrogen strategy. (IEA 2024a) At present, Sweden does not have any significant operational electrolysis capacity for green hydrogen, but it is estimated to be less than 10 MW (Fuel Cell Works 2025).

The role of green hydrogen is central in northern Sweden, where in particular the steel sector has become a pioneer in the energy transition. Several industrial-scale projects are underway in Sweden, such as H2 Green Steel, which is building an emission-free steel plant with an electrolysis capacity of 800 MW in the city of Boden. The plant aims to produce up to 5 Mt of hydrogen-produced steel by 2030. Another major project is HYBRIT, which has supplied green steel for industrial pilot use, and its commercial production is planned to begin in 2026. (IEA 2024a.)

Swedish industry is supported through programmes such as the Industrial Leap, which promotes low-carbon technologies and hydrogen-based industrial solutions. At the EU level, support mechanisms such as the Innovation Fund also contribute to the development of Sweden's hydrogen economy. Sweden is well positioned to act as a model country for green hydrogen and fossil-free industry. However, achieving these goals requires long-term infrastructure development and market planning. (IEA 2024a.)

5.4 Electricity demand, hydrogen output and emission reductions

In this chapter, the calculation framework presented in section 4.3 is applied to the electrolysis capacity targets set for 2030 in the four front-runner countries. Table 5 below presents the electrolysis capacity targets for these countries in 2030. For the Netherlands, the lower capacity target is 3-4 GW, and the more ambitious target is 6-8 GW, therefore the average of the more ambitious capacity target has been used in the calculations.

Table 5**.** Countries' electrolysis capacity targets for 2030.

Germany	10 GW
Spain	12 GW
The Netherlands	7 GW
Sweden	5 GW

To illustrate the methodology, Germany is used as an example. The calculations are based on the equations and assumptions presented in section 4.3. Using a 10 GW electrolysis capacity target and a 35 % capacity factor, the estimated annual electricity demand is 30.7 TWh. This corresponds to a hydrogen production volume of 0.61 Mt per year. Based on the assumed emission factor ranges for grey and green hydrogen, the resulting theoretical emission reduction potential is estimated to range between 5.1-8.1 Mt $CO_{2,eq}$ per year.

For other countries, the calculations have been carried out using the same formulas and assumptions as for Germany, but only the countries’ own electrolysis capacity targets (P) change. CO_2 emission reductions are presented as minimum-maximum estimates rather than single-point values because of the emission factor range. Table 6 summarizes the electricity demand, hydrogen production and theoretical CO_2 emission reduction potential for the other countries, as well as estimates of current electrolysis capacity and planned capacity for 2030.

Table 6. Results of the calculation.

Country	Current electrolysis capacity (MW)	Electrolysers in 2030 (GW)	Electricity demand in 2030 (TWh/a)	H_2 production in 2030 (Mt/a)	Theoretical CO_2 reduction potential in 2030 (Mt/a)
Germany	~57	10	30.7	0.61	5.1–8.1
Spain	~50	12	36.8	0.74	6.1–9.8
The Netherlands	~3	7	21.5	0.43	3.6–5.7
Sweden	<10	5	15.3	0.31	2.6–4.1

It should be noted that the CO_2 emission reduction values do not represent direct national emission reductions. Instead, they reflect a theoretical emission reduction potential at the EU level, assuming that the produced green hydrogen is replacing grey hydrogen within the EU hydrogen market. Overall, the results indicate that countries with larger electrolysis capacity targets, such as Germany and Spain, have the potential to contribute to higher theoretical emission reductions at the EU level. The relative significance of these reductions can be illustrated by comparing them to national emission levels, although the reductions would not necessarily occur within the respective countries. In addition, the size of the estimated reductions depends strongly on the assumed life cycle emission factors.

6 Discussion

This chapter discusses the role of green hydrogen in Europe's energy transition from wider perspective and brings together the key challenges and opportunities related to green hydrogen at the EU level. The chapter also examines the relevance of the calculated results for the deployment of green hydrogen in the selected countries and evaluates the limitations and uncertainties of the calculation.

6.1 Key findings and policy implications

This section brings together the main opportunities and challenges for green hydrogen deployment at the EU level, as presented in table 7 below. This section also discusses broader implications for EU's energy transition and energy policy. These findings help to understand how green hydrogen can realistically contribute to the European energy transition and climate targets in the period 2030-2050.

Table 7. Key findings of opportunities and challenges.

Opportunities	Challenges
- Replacement of grey hydrogen in industry - Decarbonisation of hard-to-electrify sectors - High-temperature industrial processes - Long-term energy storage and grid balancing - Reduced fossil fuel dependence - Energy security	- High production costs - Insufficient renewable electricity - Lack of hydrogen infrastructure - Slow permitting and grid connection processes - Differences in national regulations - Policy uncertainty

Overall, the findings suggest that the greatest opportunities for green hydrogen are mainly related to emission reductions in industry and other sectors that are difficult to electrify, as well as to increase the flexibility of the energy system. However, high production costs, the availability of renewable electricity and the lack of infrastructure create large-scale challenges for the deployment of green hydrogen. Overall, the results show that the role of green hydrogen in achieving the EU's climate targets depends on addressing both technological and political uncertainties.

When compared to the EU level target of reaching 50 GW of electrolysis capacity and producing 10 Mt of renewable hydrogen by 2030, the current scale of deployment remains relatively small. Despite rapid growth in recent years, installed electrolysis capacity is still far below the level required to meet the 2030 goals. From the EU policy perspective, these findings of this thesis suggest that green hydrogen will not be a primary energy source in Europe’s energy transition in the short term. Instead, it is likely to remain a complementary solution, especially in industrial processes and other sectors where direct electrification is difficult. While the emission reduction potential remains relatively small compared to all national GHG emissions, green hydrogen can still play an important role in decarbonizing industry and supporting energy system flexibility in the long term.

The results also highlight the importance of sector coupling. Achieving the planned electrolysis capacity targets, the need to increase electricity consumption is inevitable in all front-runner countries examined. Therefore, the expansion of renewable electricity generation and hydrogen production must be planned together. Without a coordinated increase in renewable capacity, large-scale use of electrolysis may put pressure on national electricity systems and therefore weaken the targeted emission reductions.

In addition, the development of hydrogen infrastructure is a key element for the hydrogen economy to function. Investments are needed, for example, in storage solutions and pipelines. EU level support mechanisms such as IPCEI projects and the EHB contribute to this development, but coordinated policy, technological development, and investment certainty will play a crucial role in achieving the targets set for the hydrogen economy.

6.2 Interpretation of calculation results

The calculation results are examined in relation to each country's current electricity consumption and total GHG emissions in order to assess the feasibility of the targets and the scale of the emission reduction potential. However, it is important to note that presented emission reduction estimates do not represent direct national emission reductions in the analyzed front-runner countries. The study does not assess whether the selected countries currently produce the same amount of grey hydrogen domestically. Instead, the calculations assume that green hydrogen replaces grey hydrogen within the EU market. Therefore, the results represent EU level substitution potential rather than country-level emission reductions. If green hydrogen is produced for export and does not replace domestic grey hydrogen production, national emissions may not decrease and could even increase due to higher electricity demand.

As mentioned earlier, hydrogen production in the EU is still mostly based on fossil fuels. In 2023, hydrogen production was approximately 7.9 Mt per year, of which more than 95 % was grey hydrogen. (European Hydrogen Observatory 2024). Therefore, green hydrogen has the potential to reduce CO_2 emissions if it replaces the production of grey hydrogen. The combined production of green hydrogen in the future by the four front-runner countries will be approximately 2.1 Mt per year, which represents only a small share of total EU hydrogen market. This highlights that although the production of green hydrogen is growing significantly, it is still at an early stage compared to fossil-based hydrogen production in the EU.

Figure 5 below illustrates the impact of the planned electrolysis capacity targets in the selected front-runner countries on electricity consumption and emission reduction potential. The dark green bars represent the increase in electricity consumption if the country reaches its own electrolysis capacity target. The lighter green bars illustrate the potential range of emission reductions achieved by replacing grey hydrogen with green hydrogen. This provides minimum-maximum estimate of how much the produced green hydrogen could contribute to emission reductions at the EU level, depending on where grey hydrogen is substituted.

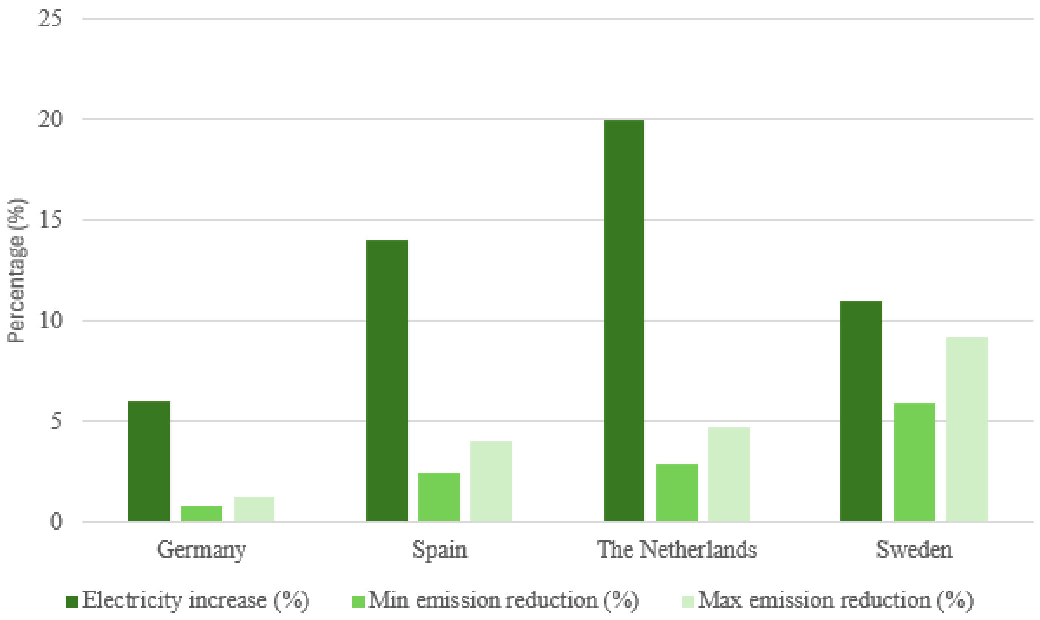

Figure 5. Impact of electrolysis capacity targets on electricity consumption increase and theoretical emission reduction potential range in front-runner countries.

Germany's target of 10 GW of electrolysis capacity by 2030 would require an estimated 30.7 TWh of electricity per year. In 2024, Germany's electricity consumption was about 500 TWh (IEA 2025c), so electrolysis would increase electricity consumption by approximately 6 %. This increase is significant, but as mentioned earlier, Germany has extensive plans for both expanding renewable energy generation and developing hydrogen infrastructure, for example through IPCEI projects, making the increase manageable. Using the applied life-cycle emission factor ranges, the potential avoided emissions are estimated at 5.1-8.1 Mt $CO_{2,eq}$ annually if the produced green hydrogen replaces fossil-based grey hydrogen produced within the EU, contributing to emission reductions at the EU level. For scale, this corresponds to approximately 0.8-1.3 % of Germany's annual GHG emissions, which totalled 649 Mt $CO_{2,eq}$ in 2024 (Statista 2025a). This helps to illustrate the overall scale of the potential impact. While the emission reduction is relatively small in relation to Germany’s total emissions, it may have a significant impact within the industrial sector.

In Spain, electricity consumption in 2024 was about 250 TWh (Statista 2025b), meaning that achieving the electrolysis capacity target would increase electricity demand by 14 %. This is a substantial increase, but Spain still has a large potential for solar and wind power, as well as an expanding hydrogen infrastructure, such as the H2Med pipeline, which makes capacity expansion technically realistic. Based on the applied emission factors, the potential avoided emissions are estimated to range from 6.1 to 9.8 Mt $CO_{2,eq}$ annually if green hydrogen replaces grey hydrogen at EU level. For scale, this represents approximately 2.5-4.0 % of Spain's total GHG emissions which were 246 Mt $CO_{2,eq}$ in 2022 (Statista 2025c). Although renewable electricity generation would need to expand considerably, the emission reduction potential is notable, especially in industrial and export-oriented sectors.

In the Netherlands, electricity consumption in 2023 was 109 TWh (Boer 2024), meaning that an additional 21.5 TWh would increase total electricity consumption by almost 20%. This represents a very substantial increase and requires significant investment in renewable electricity to achieve the targets. However, there are several green hydrogen projects planned in the Netherlands, so the increase could be achievable in the coming years. Estimated avoided emissions range from 3.6 to 5.7 Mt $CO_{2,eq}$ annually if the green hydrogen replaces grey hydrogen at EU level. In relative terms, this equals approximately 2.9-4.7 % of the Netherland's total GHG emissions which were 122 Mt $CO_{2,eq}$ in 2023 (Country Economy 2023). Although the overall national impact remains moderate, replacing grey hydrogen with green hydrogen could significantly reduce emissions in industrial sectors. In addition, the Dutch hydrogen strategy allows the production of blue hydrogen (Stam et al. 2024), which means that the country has two paths to achieving emission reductions.

In Sweden, electricity consumption was 137 TWh in 2022 (SKGS n.d), so additional 15.3 TWh would increase the total electricity consumption by 11 %. Sweden already has a strong fossil-free electricity system, so building additional capacity is more realistic than in countries where electricity production is still dominated by fossil fuels. The estimated avoided emissions range from 2.6 to 4.1 Mt $CO_{2,eq}$ annually. For scale, this corresponds to approximately 5.9-9.2 % of Sweden's total GHG emissions which were 44.4 Mt $CO_{2,eq}$ in 2023 (IEA 2025) representing a relatively larger share of Sweden's total emissions due to its lower overall emission level. However, as in the other counties analyzed, the actual national emission reduction depends on where and how green hydrogen replaces grey hydrogen use. In Sweden, hydrogen projects are mainly targeted at emission-intensive sectors such as steel production, where substitution effects may be more visible.

Based on the calculations, if the planned green hydrogen production in the front-runner countries replaces grey hydrogen production at the EU level, the combined emission reduction potential would amount approximately 17-28 Mt $CO_{2,eq}$ annually. This corresponds to roughly 0.5-0.8 % of the total annual GHG emissions in the EU, which totalled 3.3 Gt $CO_{2,eq}$ in 2024 (Eurostat 2026). Although these countries are leading the hydrogen transition, their combined contribution represents only a small share of the EU's target of reducing emissions by 55 % by 2030. Therefore, the targets for green hydrogen production must be achieved at EU level for the hydrogen economy to become an emission-free solution for sectors with high emissions

To summarize the four countries analyzed, although the electrolysis capacity targets are broadly similar in terms of gigawatt scale, their impacts on electricity consumption and theoretical emission reduction potential vary significantly. The results show that green hydrogen can contribute to emission reductions mostly in industrial sectors. However, these reductions do not necessarily occur within the countries analyzed, as they depend on where grey hydrogen is replaced within the EU hydrogen market. Germany and the Netherlands face the largest expansion requirements for renewable electricity capacity, while Sweden benefits from a low-carbon power system that enhances the relative climate benefits of green hydrogen. Spain's potential is mostly linked to renewable energy expansion and hydrogen exports.

6.3 Limitations and uncertainties of the calculation

In this thesis, the calculation is based on simplified assumptions, and the results illustrate the scale of electricity consumption and emission reductions related to green hydrogen production. The calculations do not consider all factors related to hydrogen production, such as the actual availability of renewable electricity, factors related to storage or infrastructure, production costs nor differences in electricity-related emissions between countries. Despite these limitations, the purpose of the calculations is to illustrate the potential effects of planned electrolysis capacity targets in selected front-runner countries.

A significant uncertainty is the 35 % capacity factor used in the calculations. However, the actual capacity factor is influenced by multiple factors, such as the availability and consistency of renewable electricity, which also affects the utilization rate of electrolysers. If electrolysers are used more frequently and for longer periods, the same amount of hydrogen can be produced more efficiently. Conversely, if the use of electrolysers is lower, the production of hydrogen requires relatively more electricity. (Leuthold et al. 2025.)

Regional differences between renewable energy sources can affect the capacity factor of electrolysers. Offshore wind power typically provides a higher and more stable capacity factor, while solar power has greater variability and is limited to daylight hours. (Leuthold et al. 2025.) This is also reflected in the front-runner countries. For instance, the Netherlands can utilize offshore wind power from the North Sea, whereas Spain is more dependent on solar resources. Therefore, the assumed 35 % capacity factor may overestimate hydrogen production potential in solar-dominated countries and underestimate it in wind-dominated countries.

There are also uncertainties related to emission reduction estimates, as the actual lifecycle emissions of grey and green hydrogen can vary significantly. Emissions of grey hydrogen are particularly influenced by natural gas production and transport, while emissions from green hydrogen depend, for example, on the source of renewable electricity and the use of hydrogen production technology. Therefore, emission reductions are presented in this thesis as ranges instead of single values.

In addition, the electrolysis capacity targets used in the calculation are based on national strategies and planned projects, many of which are still in the planning or investment phase. Permit processes, infrastructure development and the market situation can have a significant impact on the time frame in which projects are implemented. For this reason, the results should be interpreted as rough estimates of the possible role of green hydrogen in Europe’s energy transition.

7 Conclusions

The aim of this master’s thesis was to examine the role and development of green hydrogen in Europe's energy transition and to assess the opportunities and challenges related to its production and use. The work focused especially on the EU's policy framework in the field of green hydrogen, the hydrogen strategies of different countries, and delved deeper into the national hydrogen strategies of the four front-runner countries and their climate impacts.

This analysis provided an overview of the current state of green hydrogen in the EU by combining policy analysis, country-level strategy review, and a scenario-based calculation. The thesis clarifies how different policy approaches shape the development of green hydrogen across Europe by examining both EU level regulation and national hydrogen strategies. The comparison of selected front-runner countries shows that national strategies differ in terms of production models, infrastructure development, and reliance on imports. The results support the literature review by illustrating the scale of electricity demand, hydrogen production volumes and emission reduction potential associated with planned electrolysis capacity targets.

The study is based on qualitative literature review and does not include empirical data. The calculation framework provides order-of-magnitude estimates and relies on simplified assumptions regarding electrolysis capacity factors and electricity consumption. Also, the country-level analysis is limited to four front-runner countries which means that the findings do not fully reflect the diversity of conditions across EU Member States. Therefore, the results are only indicative rather than exact predictions.

The results of the literature review show that green hydrogen has significant emission reduction potential, especially in sectors where direct electrification is challenging. In addition, green hydrogen is expected to play an important role in future energy systems by supporting system flexibility and enabling the storage of renewable electricity.

The calculated results show that the planned electrolysis capacity targets for 2030 of the front-runner countries will cause a significant increase in their electricity consumption. At national level, the emission reduction potential remains relatively low compared to the countries' total greenhouse gas emissions, corresponding to only around 1-9 % depending on the country and the emission factor applied. In practice, these reductions depend on where grey hydrogen is replaced within the EU and may not occur directly in the countries analyzed. When considered at EU level, even if the front-runner countries fully achieved their planned electrolysis capacity targets and replaced grey hydrogen with green hydrogen, the combined emission reduction potential would remain only 0.5-0.8 % of total annual EU GHG emissions.

These findings suggest that while green hydrogen can lead to notable emission reductions, especially in energy-intensive industrial processes, it cannot alone reduce overall GHG emissions and achieve the EU’s climate targets by 2030. Therefore, green hydrogen should be considered as a complementary solution within the broader energy transition rather than a primary solution for achieving climate targets.

Major challenges remain in the large-scale deployment of green hydrogen, including high production costs, lack of infrastructure, and regulatory and market uncertainty. In particular, the results highlight the need for a more coherent EU level policies and long-term investments for the green hydrogen market to become competitive.

However, green hydrogen is an important part of long-term energy transition in the EU, and multiple plans, targets and policy instruments have already been established to support its development. Despite these efforts, the role of green hydrogen in achieving the 2030 climate targets will remain limited unless broader structural changes are made in the energy system. In the longer term, the importance of green hydrogen is expected to increase as production costs decline, markets stabilize and infrastructure develops.

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