Master’s Thesis

Spatial Disaggregation of Future Hydrogen Demand for the Industrial and Transport Sectors in Europe

In partial fulfillment of the requirements for the degree
Master of Science (M.Sc.)
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Preface

This thesis was certainly not the work of a single person. Rather, many individuals contributed and their help and support shall be acknowledged at this point.

First of all, I would like to thank **Prof. Dr. Thomas Hamacher** and **M.Sc. Beneharo Reveron Baecker**, from Chair of Renewable and Sustainable Energy Systems at the Technical University of Munich (TUM), for their open-mindedness towards my wish to conduct this master's thesis at an external research institution and their readiness to supervise it.

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Last but not least, I would like to express my gratitude to all of my friends and family who supported me throughout my journey from my first day as a master's student at TUM. Thanks a lot for your all-time encouragement and support!

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Omar Abdelrahman

Abstract

In light of climate change, hydrogen is considered one of the solutions sought to decarbonize different sectors. Hydrogen produced from renewable sources through electrolysis can play a significant role in achieving CO_2 neutrality by substituting the use of CO_2-emitting fuels in some industrial processes, such as the production of ammonia. Moreover, the integration of hydrogen into the transport sector enables the decarbonization of heavy-duty vehicles such as trucks and buses. Fuel cell electric vehicles (FCEVs) have a weight advantage over battery electric vehicles (BEVs) as the additional weight caused by heavy batteries is avoided.

In order to assess the expected disaggregation of the future hydrogen demand across Europe for the industrial and transport sectors, a regionalization tool was developed within this thesis. The tool considers 246 industrial facilities across Europe where either steel, ammonia, or refining products are produced. Based on the process-specific methodology applied in this thesis and the production values of 2020, these industrial facilities have a total estimated potential hydrogen demand of 634.5 TWh/year. This assumes a complete switch to green hydrogen and hydrogen-based alternatives in all these sites. For the transport sector, the investigated scenario assumes that 50% of passenger vehicles, 50% of trucks, and 60% of buses in the European market will be powered by hydrogen in 2050 hence rendering a total demand for road transport in Europe of 1033 TWh/year while the hydrogen demand in all of Europe's airports is expected to reach 639 TWh/year in 2050. The resulting hydrogen demand is distributed across Europe in highly populated regions or regions where refineries or ammonia production sites are located. Most of these industrial facilities are strategically located near ports and industrial hubs, making importing hydrogen easier in the future.

Keywords - **Hydrogen, Energy transition, Decarbonization, Regionalization, Hydrogen imports**

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Topic Description
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by

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Topic:
Spatial Disaggregation of Future Hydrogen Demand for the Industrial and Transport Sectors in Europe

Background/Motivation

With the aim to reach an optimal design of energy systems with large shares of renewable energies and examine energy systems transformation pathways to mitigate the effects of climate change in mind, hydrogen has recently received praise as a ray of hope forEurope's energy transition. To elaborate, the industrial and transport sectors have a considerable potential to reduce CO_2 emissions by using carbon-neutral hydrogen, which might play a crucial role in emissions reduction. Despite this, public discussions frequently raise concerns regarding large-scale supply and safety. However, it is still essential to examine the possible spatial distribution of future hydrogen demand in Europe to anticipate the future hydrogen supply infrastructure.

Goals

This thesis aims to allocate the future hydrogen demand spatially, focusing on the industrial and transport sectors in the next few decades. Therefore, the author developed methodologies for this purpose. Moreover, a tool that distributes the hydrogen demand regionally is being developed using appropriate metrics.

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Statement of Academic Integrity

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I agree to the further use of my work and its results (including programs produced and methods used) for research and instructional purposes.

I have not previously submitted this thesis for academic credit.

Munich, November, 21, 2022 Omar Mohamed

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List of Abbreviations

ATR Autothermal reforming.

BEV Battery Electric Vehicle.

BF-BOF Blast Furnace-Basic Oxygen Furnace.

CCS Carbon Capture and Storage.

CCU Carbon Capture and Utilization.

CHP Combined Heat and Power.

DRI Direct Reduction Iron.

EAF Electric Arc Furnace.

EU European Union.

FCEV Fuel-Cell Electric Vehicles.

GHG Greenhouse Gas.

LAU Local Administrative Unit.

LHV Lower Heating Value.

LPG liquefied petroleum gas.

NUTS National Administrative Subdivisions.

PEM Proton exchange membrane.

POX Partial oxidation.

PV Photovoltaic.

SAF Sustainable Aviation Fuel.

SMR Steam methane reforming.

TRL Technology Readiness Level.

Chapter 1

Introduction

1.1 Topic Motivation

The current global energy crisis pushes the need for policies to ensure that the climate goals are aligned with energy security needs. Hydrogen can improve energy security by reducing reliance on fossil fuels in end-use applications or switching from fossil-based to renewable hydrogen production. This is consistent with the increasing need to find a power generation process that can consistently and reliably replace the conventional power plant from the power grid. In light of the Paris agreement, the European climate goals to decarbonize several become apparent. European countries started taking action, such as the German government's decision to stop producing electricity through nuclear power plants, which was planned to occur in 2022 (Die Bundesregierung 2011). However, due to the current energy crisis, the last two nuclear reactors will be put on emergency reserve for 2023 (Connolly Sep. 5, 2022), and its more recent decision to stop producing electricity using coal by the year 2038 (Federal Ministry for Economic Affairs and Climate Action 2020a). In addition, the growth of a global hydrogen market can increase the variety of potential energy suppliers, improving energy security, especially for countries that import energy. By 2030, hydrogen could help prevent using 14 billion cubic meters per year (bcm/year) of natural gas, 20 Megatonne of coal equivalent per year (Mtce/year), and 360 thousand barrels per day of oil if governments adopt policies to fulfill their climate commitments (IEA 2022a).

One of the leading countries of the energy transition in Europe is Germany. The government of Germany announced that it would adopt the Climate Action Plan 2050 in November 2016. This plan represents the principles and goals of the German government's policy and its path towards becoming a Greenhouse Gas (GHG) neutral country by 2045 (Die Bundesregierung 2021), which excel over the Paris agreement, where the global challenge of reducing GHG emissions was addressed, and the GHG neutrality goal is set to 2050 (UNFCCC 2015). Moreover, the plan has different action areas to achieve this goal, namely the transport and industrial sectors. By 2030, a minimum reduction of 40% and 49% compared to 1990 values of CO_2 emissions are expected from the transport and industrial sectors, respectively (BMUB 2016).

The industrial and transport sector emitted around 46% of the global CO_2 emissions in 2020 (Figure 1.1). They are both considered the second largest carbon emitter after power generation in the energy sector, with a share of 23% each (IEA 2020). These two sectors must be decarbonized to achieve the climate policy goals. About 38% of the industrial sector's emissions are directly related to production processes of raw materials industries, such as those used to make steel, basic chemicals, cement, and lime, and not from energy use. While many options are generally available, the industrial sector presents particular challenges in reducing emissions. For instance, these processes can be replaced by new industrial technologies and techniques, and carbon capture and utilization (CCU) can be used to lower CO_2 emissions. However, if emissions are unavoidable, long-term carbon capture and storage (CCS) may be required to reduce them (BMUB 2016). Moreover, this sector needs to drastically cut its CO_2 emissions as there have been no significant reductions over the past two decades (Agora Energiewende und Wuppertal Institut 2019). The foundation for cutting emissions and achieving climate goals relies on reducing final energy consumption through improved efficiencies, increased renewable energy capacity, and synthetic energy carriers (Teske 2019).

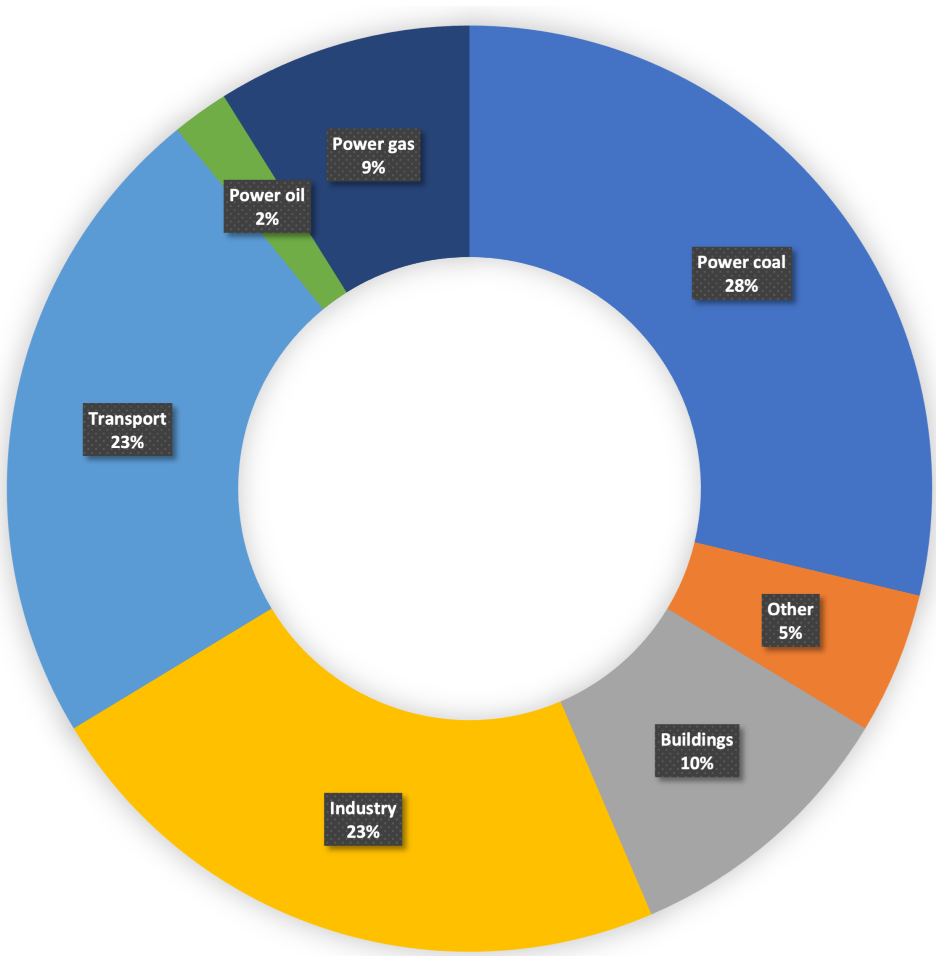

Figure 1.1 Global CO_2 emissions by sector (IEA 2020)

Progress is being made in a few significant new hydrogen applications in several sectors. In the industrial sector, announcements for new steel projects are expanding quickly one year after the first demonstration project for using pure hydrogen in direct iron reduction (IEA 2022a). Germany witnessed the debut of the first fleet of hydrogen fuel cell trains in the transport sector (Alstom 2022). The use of hydrogen and its derivatives in shipping has also been the subject of several demonstration projects, and major companies are already forming strategic alliances to guarantee the supply of these fuels. The use of hydrogen and ammonia in the energy sector is getting more attention; projects that have already been announced could have almost 3.5 GW of capacity by 2030 (IEA 2022a). If challenges are addressed quickly, significant volumes of hydrogen could be traded by the end of this decade. Some significant steps in establishing a global hydrogen market were reached in 2022 with the shipment of the first-ever container of liquefied hydrogen from Australia to Japan in February (The Australian Trade and Investment Commission Feb. 14, 2022), followed by the shipment from UAE to Germany in October (Deutsche Welle Oct. 22, 2022).

The momentum behind hydrogen has accelerated due to the global energy crisis sparked by the Russian-Ukrainian war. In order to lessen their reliance on fossil fuels, many European governments have to consider low-emission hydrogen as a solution. Hydrogen produced from a renewable source presents an opportunity to improve energy security while achieving decarbonization goals. The German government released a National Hydrogen Strategy in 2020, highlighting hydrogen as a potential decarbonization solution (Die Bundesregierung 2020).

1.2 Research Objectives

Hydrogen has recently received praise as a ray of hope for Europe's energy transition. As the goal is to reach an optimal design of energy systems with large shares of renewable energies, examining the energy systems transformation pathways to mitigate the effects of climate change has become crucial. Despite this, public discussions frequently raise concerns regarding large-scale supply and safety. However, it is still essential to examine the possible spatial distribution of future hydrogen demand in Europe to anticipate the future hydrogen supply infrastructure, storage capacities, and installed electrolyzer location and capacity.

This thesis aims to allocate the future hydrogen demand spatially, focusing on the industrial and transport sectors in the next few decades. Possible point sources are sought to achieve a high-resolution demand representation. The following research questions are covered in this thesis:

- How are the industrial and transport sector's hydrogen demands spatially distributed across Europe?
- How is the future hydrogen demand located across Europe compared to the geographical distribution of renewable energy potential?

Chapter 2

Technical Background

This chapter provides an overview of the main characteristics of hydrogen and the state of art technologies to produce, transport, and store hydrogen. Section 2.1 goes over the basic properties of hydrogen. Different paths to produce hydrogen are presented in Section 2.2. A brief explanation of how to transport and store hydrogen is provided in Sections 2.3 and 2.4 consecutively. Section 2.5 discusses the possible future applications of hydrogen. Finally, in Section 2.6, the role of hydrogen in the European energy transition strategy is presented.

2.1 Hydrogen Characteristics

Hydrogen (H_2), a colorless, odorless, tasteless gaseous substance, is the simplest member of the family of chemical elements (Linde 2021). Under normal circumstances, hydrogen gas is a loose collection of hydrogen molecules composed of two atoms, a diatomic molecule. In its gaseous monatomic form (H_2), hydrogen is a highly flammable gas that reacts spontaneously with oxidizing elements such as oxygen, chlorine, or fluorine. As hydrogen is easily ignitable, it burns with a light blue, nearly undetectable flame once lit. The vapors are lighter than the air and ignite easily at various vapor/air concentrations. Hydrogen is not toxic but a simple asphyxiate displacing oxygen in the air. Hydrogen is the first element on the periodic table and the most abundant element in the universe. It is more than three-quarters of all the matter. Pure hydrogen does not naturally occur on our planet. However, it occurs in vast quantities as part of the water in oceans, ice packs, rivers, lakes, and the atmosphere. As part of innumerable carbon compounds, hydrogen is present in all animal and vegetable tissue and petroleum (Jolly 2022). At standard conditions, hydrogen is a gas. However, it becomes liquid at very low temperatures and under high pressures.

Of all gases, hydrogen gas is the lightest. Its density is the lowest compared to all other gases (0.09 $\mathrm{kg\,cm^{-3}}$ at 20 °C and 70.79 $\mathrm{kg\,m^{-3}}$ in the liquid state. Under normal conditions (standard temperature and pressure), it is non-toxic and non-metallic. Hydrogen has a boiling point of 252.8 °C and a melting point of 259.2 °C (Linde Gas 2021). Due to these characteristics, related hydrogen distribution and storage challenges are covered in greater detail in Sections 2.3 and 2.4. Hydrogen has a high Lower Heating Value (LHV), which measures the amount of thermal energy that can be produced during combustion per unit of mass or volume. In contrast, the LHV considers energy losses such as water vaporization, thus also known as net calorific value.

Under normal circumstances, hydrogen is also considered a stable, non-reactive substance. However, in terms of safety, like other energy carriers, hydrogen presents certain safety risks as detonations when considered on an extensive scale application. Its small size makes hydrogen easy to diffuse into other materials or sealings. Compared to natural gas, hydrogen has a nearly seven times wider igniting range and a higher leakage rate. Therefore, more upgrades to flow control and leak detection systems might be required, as recommended in the IEA report about the global hydrogen review (IEA 2022a). Moreover, hydrogen is lighter than air and does not self-ignite; instead, it rises into the air. Outdoors, hydrogen is not explosive as it has a high diffusion coefficient and spreads quickly in the surrounding area (Linde Gas 2021).

2.2 Hydrogen Production

Hydrogen can be extracted from water, biomass, fossil fuels, or a combination. Natural gas is the primary source of hydrogen production, contributing about 75% of the roughly 70 million tonnes of hydrogen produced annually worldwide. Gas is followed by coal, which accounts for an estimated 23% of global hydrogen production, with a small fraction produced from electricity and oil. In Figure 2.1, hydrogen production processes are illustrated. The hydrogen produced from fossil fuels, primarily natural gas, is called 'grey' hydrogen. This production process emits a significant amount of CO_2 emissions: 10 tonnes of carbon dioxide per tonne of hydrogen (t_{CO2}/t_{H2}) when using natural gas, 12 t_{CO2}/t_{H2} when using oil products, and 19 t_{CO2}/t_{H2} when using coal (IEA 2019). It is called 'blue' hydrogen when decarbonizing this process by adding a CCS unit. Finally, 'green' hydrogen, considered the ultimate goal, is made from water electrolysis using renewable energy sources (van Renssen 2020b).

Currently, most hydrogen is made from fossil fuels without CO_2 capture in a process called pyrolysis. Although it is not sustainable, this method of producing hydrogen is the least expensive (IRENA 2019). A comparison between hydrogen production costs by production source is illustrated in Figure 2.2. Even though several technical and economic factors affect pyrolysis cost, the two most significant ones are gas prices and capital expenses. Between 45% and 75% of production costs are related to fuel prices nowadays, which is the most critical factor. Due to low gas prices, some of the lowest costs for producing hydrogen can be found in North America, Russia, and the Middle East. On the other hand, the cost of producing hydrogen is higher for gas importers like Japan, Korea, China, and India due to higher gas import prices (IEA 2019).
The German government has debated the role of blue hydrogen, made from decarbonized natural gas, compared to green hydrogen, which is made from renewable energy and electrolysis, as it develops a hydrogen strategy (Dickel 2020). One of the most prominent advocates of blue hydrogen is the oil and gas sector, which

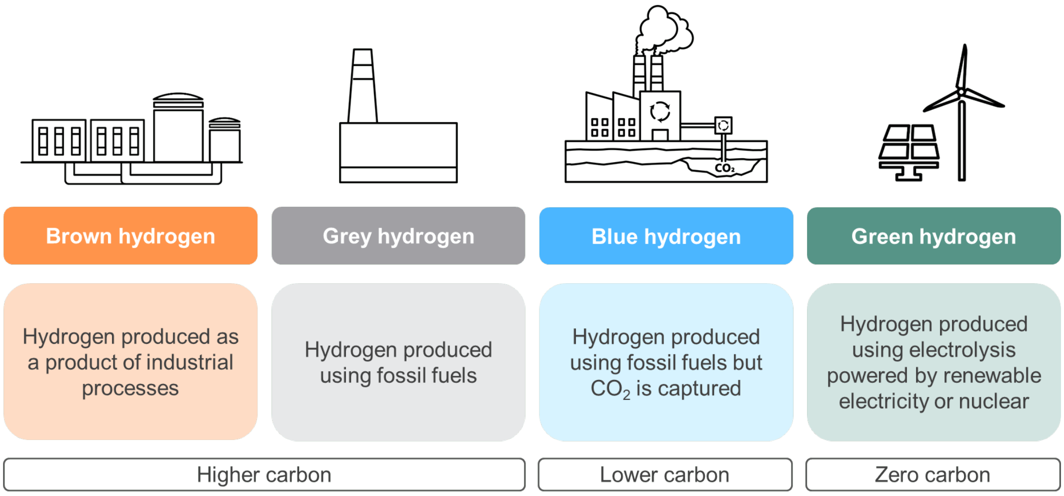

Figure 2.1 Hydrogen production processes (Wilton International 2019)

can use its current infrastructure for gas production, transportation, and storage while moving toward clean fuels (IEA 2019). Geological structures, such as abandoned oil and gas fields and saline aquifers, can be used to capture and store the emitted CO_2 when producing blue hydrogen (Gibbins and Chalmers 2008). At the same time, many claims that to develop a market for what will ultimately be green hydrogen, blue hydrogen is necessary. However, there are differences within the climate community. The issue with blue hydrogen from a climate perspective is that it depends on CCS and natural gas. First, commercially viable CCS is still a work in progress rather than a reality. Secondly, carbon capture will never be 100% efficient (van Renssen 2020b). CCS efficiencies are expected to reach a value between 85% and 95% at best, which means that 5% to 15% of all CO_2 is leaked (IRENA 2019).

2.2.1 Production Based on Fossil Fuels

Steam methane reforming (SMR) is the primary process for producing hydrogen. Partial oxidation (POX) and Autothermal reforming (ATR), a combination of SMR and POX, are less frequent. The process of steam reforming is used to separate hydrogen from natural gas. Heavy fuel oil and coal are partially oxidized to obtain hydrogen (IEA 2019). SMR is frequently used for various purposes, such as bulk hydrogen production, ammonia synthesis, and oil refining. Steam reforming can also be used with other feedstocks, such as liquid hydrocarbons such as liquefied petroleum gas (LPG) or naphtha, even though natural gas is the most frequently used feedstock (Fuel Cells and Hydrogen Observatory 2022). The price of the feedstock is essential and should be considered when choosing the best option. In the steam reforming process, the feedstock and steam engage in a series of reactions that primarily produce hydrogen, carbon dioxide, and carbon monoxide (García 2015). The emission factor for hydrogen produced by SMR is approximately 9.5 kilograms of CO2 per kilogram of hydrogen (IRENA 2019).

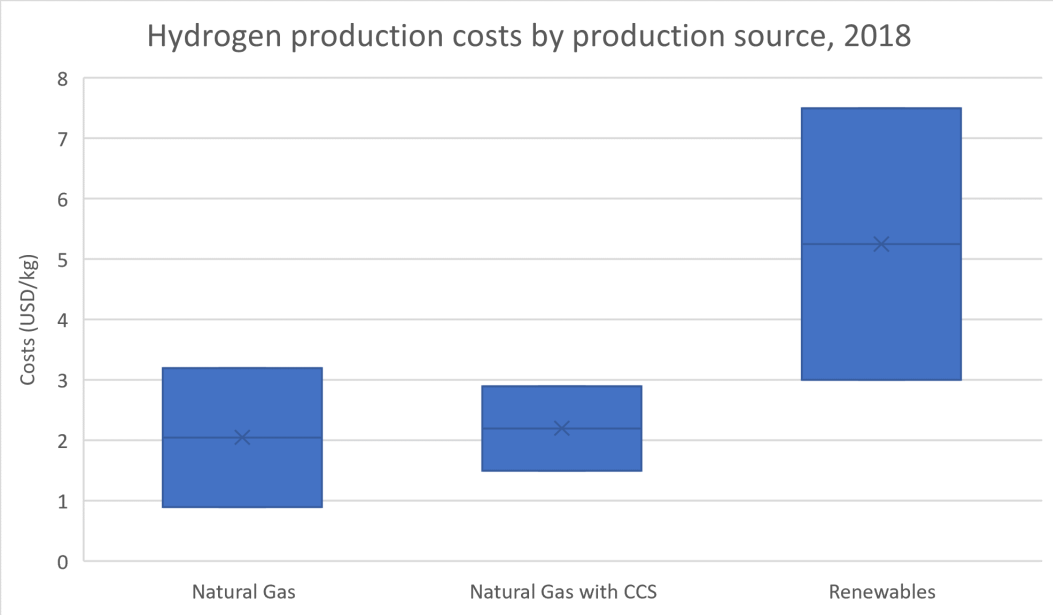

Figure 2.2 Hydrogen production costs by production source (IEA 2019)

Both SMR and ATR hydrogen production is compatible with CCS. Utilizing CCS with SMR plants can reduce carbon emissions by up to 90% and increase production costs. However, CCS is essential to decarbonizing the sizable SMR fleet currently in use (IEA 2019).

2.2.2 Production Based on Biomass

Thermochemical, biological, and electrochemical methods are currently used for biomass-to-hydrogen conversion to produce hydrogen from lignocellulosic biomass, a novel option based on renewable resources. The best yield for the production of hydrogen is provided by the thermochemical process, particularly gasification, partial oxidation, and steam reforming. The best compromise is steam gasification because it can be used with wet and dry biomass and does not need an oxidizing agent. In terms of biological conversion, dark fermentation is preferable to photo-fermentation because it uses less energy. Furthermore, biomass can be processed electrochemically. A biomass-based hydrogen production is a promising option that increases the capacity to produce hydrogen, but it needs to be improved to make more competitive volumes in larger sizes. If combined with CCS, biomass conversion might become CO_2-negative (Lepage et al. 2021). This thesis does not go into great detail regarding biomass-based hydrogen production.

2.2.3 Production Based on Water

Hydrogen and oxygen are separated from water through the electrochemical process known as water electrolysis. As it requires the least amount of electrical energy and has been around for more than 230 years, electrolysis is still the most straightforward and effective method for producing hydrogen (Smolinka et al. 2022). Today's electrolyzer systems have an efficiency that varies from 60% to 81% depending on the technology and load factor. Water electrolysis accounted for less than 0.1% of the world's hydrogen production in 2021. However, several demonstration projects have been developed recently due to the growing interest in electrolytic hydrogen and the falling costs of renewable electricity, mainly from solar PV and wind (IEA 2019). In 2021, the electrolyzer installed capacity is increased by 210 MW from 2020 values, reaching 510 MW. With nearly 40% of this capacity developed in China and roughly a third in Europe, the global electrolyzer capacity could surpass 1 GW by the end of 2022 and reach around 1.4 GW, nearly tripling the 2021 level (IEA 2022a).

Proton exchange membrane (PEM) electrolyzers made up one-quarter of the installed capacity in 2021, with alkaline electrolysis accounting for almost 70%. Although emerging, less developed technologies than alkaline and PEM electrolyzers, such as solid oxide electrolysis cells and anion exchange membrane electrolysis, make up only a small portion of the installed capacity today (IEA 2022a). An alkaline water electrolysis cell consists of a cathode, an anode, and a separator for hydroxide ions, and water molecules are located between the two chambers. In PEM electrolysis, a proton-conducting membrane allows hydrogen ions to diffuse through it.

A total of 3600 GWh of electricity and 617 million cubic meters of water would be required to produce all of today's hydrogen production, around 70 Mt_{H2}. This is more than the annual electricity production of the European Union and corresponds to 1.3% of the water consumption of the global energy sector today and roughly twice the current water consumption for hydrogen from SMR. For every kilogram of hydrogen gas produced, approximately 9 liters of water are also consumed, yielding an additional 8 kg of oxygen, which can be used either on a small scale in the medical field or on a larger scale in the industry (IEA 2019).

2.3 Hydrogen Transport

Despite hydrogen's considerable potential to reduce carbon emissions, its transport and storage are still up for debate. In this section, the challenges facing hydrogen diffusion are discussed as well as possible ways of transport. Section 2.4 presents the challenges and opportunities from a storage point of view.

Hydrogen can be produced near the source of production, such as electricity or natural gas, or close to the point of consumption. For large hydrogen consumers such as refineries and plants that produce ammonia, methanol, and hydrogen peroxide, on-site captive hydrogen production is the most common method of hydrogen supply. The high volume of hydrogen consumed in these cases justifies the investment in a dedicated hydrogen generation unit (Fuel Cells and Hydrogen Observatory 2022). Despite the substantial investment dedicated to an on-site hydrogen generation unit, there is an advantage in that, which is the fact that a minimal supply infrastructure for distribution is required.

A transmission network typically transports hydrogen produced near a production source to final consumers, such as residential customers and hydrogen refueling stations. There are two commonly used transmission methods for hydrogen: trucks and pipelines. Gaseous hydrogen transportation via pipelines is the least expensive transmission for long distances and high demand (Fuel Cells and Hydrogen Observatory 2022). However, the forecasted amount of hydrogen in carbon-neutral scenarios for Europe exceeds the capacity of the current hydrogen infrastructure in Europe. The cost of a new hydrogen transmission pipeline network entails significant investment. However, it might be possible to retrofit the current natural gas distribution networks to transport hydrogen (Federal Ministry for Economic Affairs and Climate Action 2020b). In addition to the generation unit, a typical hydrogen transport system includes a conversion component such as a compressor or liquefaction unit, transmission and distribution components such as long-distance high-pressure transport pipeline infrastructure and local low-pressure distribution network, and storage capacities. On the other hand, trucks are more feasible for low-demand cases, as they can transport hydrogen in liquid and gaseous forms (European Commission, Directorate-General for Energy 2020). For longer distances, it is economically and environmentally feasible to use pipelines in transporting hydrogen, while trucks are considered a more suitable option for short distances, i.e., 100 km (Christina Wulf et al. 2018).

An alternative possibility is to use ammonia as a hydrogen carrier. Transporting ammonia is much simpler than hydrogen; however, a further step is required to liberate the hydrogen before final consumption, except when ammonia can be used directly as a final product by the consumer. Additional energy and costs are required, which must be weighed against the cheaper transportation options. Even taking into account the costs of converting hydrogen into ammonia and back again, the transmission of hydrogen as ammonia is a more economical option for longer distances than 1500 km, particularly if the hydrogen needs to be transported overseas (IEA 2019).

2.4 Hydrogen Storage

Today, hydrogen is mainly used for small-scale mobile and stationary applications and is typically stored as a gas or liquid in tanks. However, significant hydrogen storage capacities are needed to balance the supply and demand for hydrogen to play an essential role in the energy system. Hydrogen storage may be necessary for a brief time before shipping, for instance, at an export terminal. At vehicle refueling stations, hours of hydrogen storage are required, but days to weeks of storage would help users protect against potential mismatches in hydrogen supply and demand. If hydrogen were to bridge significant seasonal changes in electricity supply or heat demand or provide system resilience, much longer-term and larger storage options would be necessary (IEA 2019).

The volume to be stored, the duration of storage, the required speed of discharge, and the geographic availability of various options all play a role in determining the best storage medium. Numerous technologies are better suited for short-term and small-scale storage, such as pressurized vessels and liquid hydrogen tanks. In contrast, geological storages, such as salt caverns and depleted gas fields, are generally the best option for large-scale and long-term storage (European Commission, Directorate-General for Energy 2020). In a potential future hydrogen economy, large-scale hydrogen storage is essential. Despite being used on a large industrial scale, gaseous hydrogen storage in salt caverns is not feasible everywhere due to different geological conditions.

Consequently, alternate storage techniques are required. In terms of storage density, cost, and safety, it has been discovered that using some storage technologies, such as liquid hydrogen, methanol, ammonia, and dibenzyl toluene, is advantageous. These high-density storage technologies' variable costs are primarily related to either a high electricity requirement for the storage process or a high heat requirement for the hydrogen release process. However, most of these storage technologies are still being researched very actively, suggesting that significant advancements are still needed (Andersson and Grönkvist 2019).

2.5 Hydrogen Uses

In 2021, the world's demand for hydrogen increased by 5% from the previous year to over 94 million tonnes (Mt), compared to a pre-pandemic level of 91 Mt recorded in 2019. Most of the growth in hydrogen use from 2020 was in conventional applications, particularly chemicals, with a nearly 3 Mt increase, and refining, with about 2 Mt increase. The Covid-19 pandemic had a significant impact on these subsectors, particularly refining. Hydrogen demand increased in 2021 as the activity impacted by the lockdowns and the general economic slowdown began to recover. Most of the supplied hydrogen was produced using fossil fuels, which had no benefit for reducing carbon emissions to mitigate the effects of climate change. Refer to Section 2.2 for more information about the different hydrogen production processes. In 2021, there was very little demand for hydrogen in new applications, such as heavy industry, transportation, power generation, the building sector, or the production of fuels derived from hydrogen. This demand was only about 40 kilotonnes (kt) of hydrogen (or 0.04% of the world's total demand for hydrogen). This was primarily for road transport, which saw a sizable increase, particularly in heavy-duty vehicles (IEA 2022a).

The potential applications and associated challenges facing hydrogen in various sectors are discussed in the following section.

2.5.1 Industrial Sector

The most promising candidates for identifying hydrogen potentials are those industrial sectors that are both energy and carbon-intensive and are challenging to electrify. The industrial sector needs to be addressed explicitly at this time because complex industrial facilities run for 50 to 70 years and set the course for the future (Agora Energiewende und Wuppertal Institut 2019). In the coming years, many necessary refurbishments will present an opportunity to upgrade the facilities to more environmentally friendly production methods.

Currently, the primary industrial uses of hydrogen are the refining sector, with a demand of 40 Mt of hydrogen, the production of ammonia, which requires 34 Mt of hydrogen, methanol, with 15 Mt, and Direct Reduced Iron (DRI) in the steel industry, with 5 Mt (IEA 2022b). In 2020, 90% of Europe's hydrogen was used as a feedstock for producing methanol, ammonia, and refined fuels (Cihlar et al. 2020). The majority of the hydrogen used in industry today is produced from fossil fuels (natural gas or coal), resulting in 630 Mt of net direct CO_2 emissions in 2021, which accounts for 7% of all industrial CO_2 emissions (IEA 2022a).

However, uncertainty surrounds the outlook for future hydrogen demand as the full consequences of the Russian-Ukrainian war are still unknown. The instability in the world's energy markets severely suppresses the recovery in industrial activity seen in 2021.

Figure 2.3 shows the share of the global hydrogen demand per industrial sector. By meeting these demands, emissions from industrial processes in refineries, ammonia, and steel plants can be significantly reduced. The steel industry is chosen over other subsectors, such as methonal production, which has a more significant share in the current hydrogen demand due to the vast forecasted growth for the hydrogen demand in the steel industry.

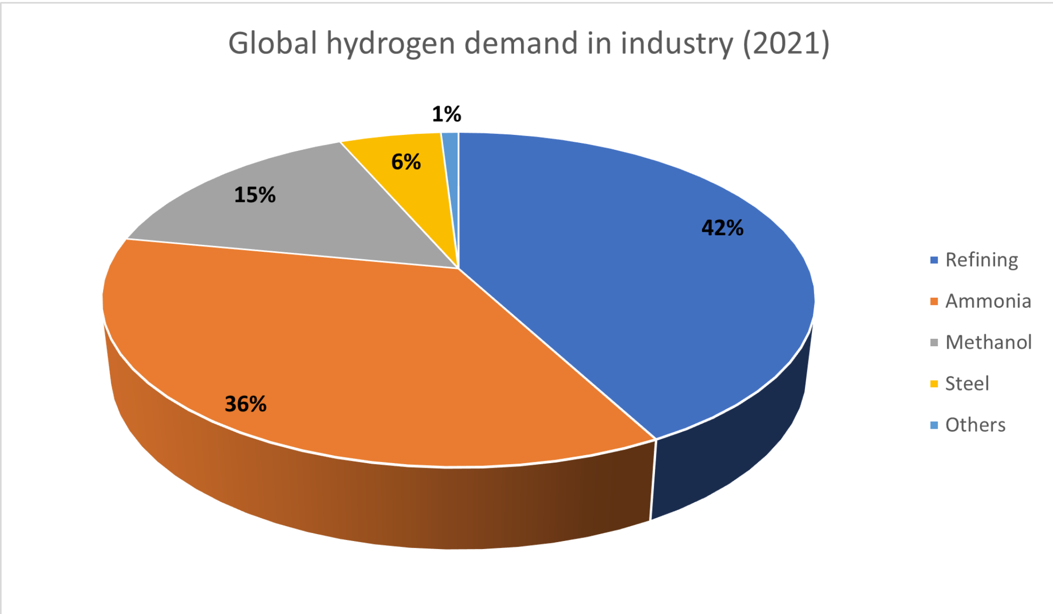

Figure 2.3 Global hydrogen demand in industry (IEA 2022b)

Refining

The oil refining industry is Europe's largest producer and consumer of hydrogen. Hydrogen is primarily used in refineries for hydrocracking and hydrotreating processes such as hydrodesulfurization, which is required to meet the fuel sulfur content targets. They must be reduced due to legislative requirements, thus increasing the sector's hydrogen consumption. Hydrotreatment is one of the crucial steps in the refinement of diesel. While long unsaturated products are converted into products with a lower molecular weight than feed through the process of hydrocracking (Fuel Cells and Hydrogen Observatory 2022). Hydrocracking is the most common hydrogen-consuming process, needing around 27 kg_{H2}/t of the product. Hydrotreating processes usually require only around 1.8-4.5 kg_{H2}/t of the product (Welder, Ryberg, et al. 2018).

After the pandemic year (2020), which had a braking effect on refining activity as demand for mobility, the primary consumer of oil products, fell sharply, and hydrogen demand in refining reached 40 Mt in 2021. More than 200 Mt of CO_2 were emitted in 2021 due to the nearly complete reliance on fossil fuels to produce the hydrogen used in refineries. Most low-emission hydrogen refining projects currently in development, or about two-thirds of the total production capacity of such projects, are located in Europe (IEA 2022a).

The current energy crisis may present an opportunity to speed up the adoption of low-emission hydrogen, mainly hydrogen derived from renewable sources, in refineries in the area. This situation helps bridge the cost gap between hydrogen production based on renewable energy sources and natural gas. This expands the opportunity to increase the use of hydrogen produced from renewable sources in European refineries to reduce the demand for natural gas. It is unclear how long the current situation will last or whether it will be enough to drive projects toward execution.

Ammonia

The ammonia industry is Europe's second-largest hydrogen consumer after refineries. The method for producing ammonia involves a synthesis of nitrogen and hydrogen. The production companies of ammonia are the biggest consumers of hydrogen in the chemicals industry. Ammonia is a critical component in producing fertilizers and nitric oxide, a by-product used to produce nitric acid. Sodium carbonate, also known as soda ash, explosives, hydrogen cyanide, synthetic fabrics, and other products are also produced using ammonia (Fuel Cells and Hydrogen Observatory 2022).

The majority of the world's ammonia demand, roughly 70%, comes from mineral nitrogen fertilizers, with the remaining 30% going to various industrial uses like explosives, synthetic fibers, and specialty materials. In 2021, the world produced about 190 Mt of ammonia, which accounted for about 34 Mt of the global hydrogen demands, or roughly one-third of those in the industrial sector. The air is the nitrogen source in ammonia (NH_3), whereas fuels used as feedstock are the source of hydrogen (IEA 2022a). It takes about 175 kg of hydrogen to produce one tonne of ammonia (Welder, Ryberg, et al. 2018).

The majority of feedstock today comes from fossil fuels. About 70% of the ammonia produced globally comes from natural gas, and most of the remaining 30% comes from coal (IEA 2022a). The importance of addressing ammonia production to combat climate change is highlighted because it only contributes to 1.8% of global CO_2 emissions and 2% of the demand for fossil fuels. On average, 2.2 t of CO_2 are emitted while producing one tonne of ammonia (Monash University June

21, 2021). Electrolysis and CCS are essential technologies that can significantly reduce ammonia emissions, leading to low-emission production. If enough green hydrogen is available, the production process does not need to be altered, only the feedstock needs to be changed, and ammonia production could theoretically be decarbonized. As a result, fertilizer production with renewable ammonia is regarded as a viable, early market opportunity for green hydrogen (Brown Aug. 2019).

Steel Industry

The production of one tonne of crude steel currently results in about 1.4 t of direct CO_2 emissions (IEA 2019). The steel industry accounts for 7% of the global CO_2 emissions (Holappa 2020) and 4% of all the CO_2 emissions in Europe (Bellona Europa 2021). According to the Paris Agreement, the European steel industry must cut its CO_2 emissions by 80 to 95% (Rechberger et al. 2020). The decarbonization of this sector could be accomplished in several ways, either by improving the efficiency of the current production processes or by steel recycling which will not be possible for industries that demand high-quality steel, like the automotive industry; new steel will always be required due to impurities like copper that accumulate over time, or by using CCS directly at the steel plant or in the production of hydrogen (Bhaskar, Assadi, and Nikpey Somehsaraei 2020).

DRI is a process for turning iron ore into steel using hydrogen as a reducing agent. Utilizing both existing and new process technologies, DRI provides a route for the use of hydrogen in steel production. For the chemical reduction of iron ore for steelmaking, conventional DRI technology uses a mixture of carbon monoxide and hydrogen produced from fossil fuels. Today's industrial hydrogen demand, around 5 Mt, makes DRI a vital opportunity to cut emissions from current industrial applications. Green hydrogen can also reduce emissions from current steel production methods. Depending on the furnace design and desired blending rate, it can be blended into conventional DRI units, replacing natural gas and coal with only minor equipment modifications (IEA 2022a). The DRI process is much quicker with hydrogen than with coal; hence the beneficial side effect of greater time efficiency still applies (Liu et al. 2021). According to (Bataille et al. 2018), this efficiency improvement provides an additional way to utilize renewable energy production peaks that would otherwise go unused. However, due to the expensive natural gas prices in Europe, DRI is primarily used outside of Europe (Bellona Europa 2021).

Considering that the steel industry has only occasionally used hydrogen (Prognos, Öko-Institut, and Wuppertal-Institut 2020), hydrogen can be used in the production of steel in three different ways: as an auxiliary reducing agent in the blast furnace-basic oxygen furnace BF-BOF route (H2-BF), as the sole reducing agent in the DRI process (H2-DRI), or as a heat source during the production process (Liu et al. 2021).

In Europe, 60% of the steel is produced via the BF-BOF route, also referred to as the primary production route (European Steel Association 2021). The blast furnace and the coke plant are the primary sources of emissions. Coking coal, produced at the coke plant, is used in the blast furnace to heat the environment and reduce iron.

Because it uses less coal and only produces water when reacting with iron ore instead of carbon dioxide, using hydrogen as an auxiliary reducing agent (H2-BF) can lower emissions from both the coke plant and the blast furnace. Currently, pulverized coal, oil, natural gas, or a combination of these are the most popular auxiliary reducing agents, resulting in CO_2 emission. However, for technical reasons, it is not feasible to operate a blast furnace solely on hydrogen, so H2-BF is frequently viewed as a step-by-step transition to using hydrogen as the sole reducing agent (H2-DRI) to reduce emissions in the short term. Using green hydrogen along the BF-BOF route can, at most, result in a 21% reduction in emissions. Similar emission reduction values can be achieved using blue hydrogen (Bellona Europa 2021).

Besides the BF-BOF steelmaking process, there is the Direct Reduction Electric Arc Furnace (DR-EAF) route. To create direct reduced iron, also known as sponge iron, iron ore is reduced with hydrogen while in a solid state, thus the direct name reduction. The sponge iron is placed inside an EAF, where electrodes produce a current that melts the sponge iron and turns it into steel. Steel production requires some carbon, so it is necessary. This carbon can be derived from sources like biomethane, pulverized coal, or other biogenic carbons. The EAF route is typically used for steel recycling, while the BF-BOF route is for new steel production (Bellona Europa 2021).

Future technological advancement in DR-EAF is also anticipated. By 2030, 30% of the natural gas used in DR-EAF production will be replaced by pure hydrogen obtained from external sources through electrolysis, which could be done with minimal equipment changes (Chevrier August, 2018). If this ambitious development were to be realized, the hydrogen demand for producing iron and steel would be between 9 and 11 Mt_{H2}/year, with about 4.5 Mt_{H2}/year coming from renewable electricity sources and the remaining from natural gas. This would require 230 TWh of electricity annually, roughly equal to Turkey's current total electricity consumption. However, natural gas would still be crucial for providing the remaining hydrogen in 2030, leading to a 31 bcm/year natural gas demand, roughly equivalent to Spain's current natural gas consumption (IEA 2019).

Long-term CO_2 emissions from primary steel production would be drastically reduced according to a Paris-compliant pathway. As long as the electricity was generated using renewable energy sources, using the 100% hydrogen DRI-EAF route for all primary steel production would eliminate CO_2 emissions. 47 to 67 Mt_{H2}/year would be needed for this. To produce this much hydrogen, more than 2,500 TWh/year of electricity would be required, which is roughly equal to the current electricity consumption of India, Japan, and South Korea. As a feedstock for electrolyzers, a sizeable but manageable amount of water would also be needed: about 0.6 bcm/year, or about 1% of the energy sector's current water consumption (IEA 2019).

If the IEA's prediction of 400% increase in hydrogen demand is accurate, scaling up will be difficult. In addition, even though the price of green hydrogen is expected to drop by 30% by 2030, switching to innovative steelmaking methods is expected to increase costs by 10% to 50% (IEA 2022a). Furthermore, (Prognos, Öko-Institut, and Wuppertal-Institut 2020) express doubts about hydrogen's ability to satisfy the entire market for reducing agents because, based on current knowledge, specific carbon components might still be required for metallurgical purposes.

To summarize, many cleaner pathways for primary steel production would significantly cut CO_2 emissions. These fall into two categories: By utilizing low-carbon energy sources and reduction agents, most commonly hydrogen. This falls under the “CO_2 avoidance" pathways which aim to avoid most CO_2 emissions entirely. In contrast, "CO_2 management" pathways aim to recover and manage the CO_2 associated with conventional fossil fuel-based routes, typically through the direct application of CCS.

2.5.2 Transport Sector

Both directly in fuel cells and in internal combustion engines, as well as indirectly, when renewable hydrogen is used to create other, more complex synthetic fuels, hydrogen can also be used as a fuel. The demand for hydrogen in transportation surpassed 30 kt in 2021. However, only 0.03% of the world’s hydrogen demand comes from transportation, and hydrogen only accounts for 0.003% of all transport energy (IEA 2022a). This section will cover the hydrogen applications in the transport sector and the associated challenges.

Road Transport

The largest source of hydrogen demand in the transport sector comes, by far, from road vehicles. Due to their high annual mileage and heavy weight, trucks and buses consume most of this demand. The estimated hydrogen demand from commercial vehicles, such as vans and trucks, has increased significantly in 2021, more than 60 times from 2020. For the first time in 2021, commercial vehicle hydrogen demand surpassed the demand for buses and accounted for 45% of all hydrogen demand in the transportation sector (IEA 2022a). In Figure 2.4, the hydrogen demand per vehicle type is illustrated.
Over 50,000 fuel-cell electric vehicles (FCEV) are on the road as of 2021 (IEA 2022a). However, due to the high degree of uncertainty in the cost development associated with fuel cells, tanks, hydrogen generation, and the competition from battery electric vehicles that come with significantly higher efficiency ratings, the use of hydrogen for passenger cars is a topic of contentious debate (Hebling et al. 2019). One of the challenges facing the usage of hydrogen for road transport vehicles is compressed tanks, which are used in cars and trucks rather than at gas stations. They have a higher energy density than lithium-ion batteries, allowing them to travel farther than battery-electric vehicles (IEA 2019). Therefore, one of the most promising applications for fuel cells is in logistics, trucks, buses, and rail transport (IEG, ISI, and IKTS May 2021). However, the lack of a widespread network of hydrogen refueling stations poses a challenge for fuel-cell electric vehicles. In 2021, there were 91 hydrogen refueling stations in Germany, compared to more than 14,000 gas stations (Fuel Cells and Hydrogen Observatory 2022).

Rail Transport

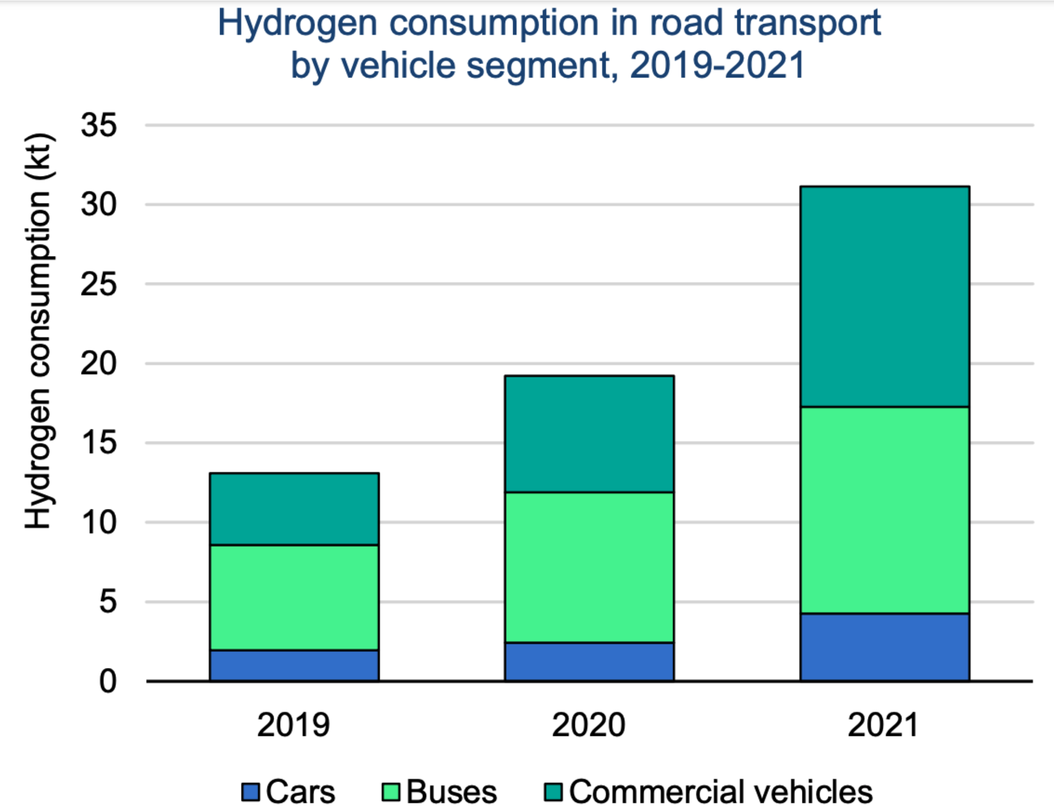

Figure 2.4 Hydrogen consumption in road transport per vehicle type. Note: Commercial vehicles include light commercial vehicles, medium-duty trucks, and heavy-duty trucks. (IEA 2022a)

Due to the success of the hydrogen-fueled passenger train trials conducted in Germany, the first fleet of 14 fuel-cell trains was deployed in Bremervoerde, Lower Saxony, in August 2022. Additionally, the first hydrogen train filling station in the world is constructed. Once completed, the hydrogen filling station will replace the current mobile filling system. It is one of the largest hydrogen refueling stations in the world, with a nominal capacity of 1,600 kg per day. The 14 regional trains powered by hydrogen that Alstom provided will receive daily and round-the-clock refueling there. The multiple-unit trains will be able to operate without emitting any emissions on the EVB network all day long thanks to a range of 1,000 km and just one tank fill (Alstom 2020).

The Coradia iLint, developed by Alstom, is the first passenger train in the world to use a hydrogen fuel cell to generate traction power. Low noise levels are produced by this zero-emission train, which only emits steam and condensed water as exhaust. The iLint is unique for its fusion of various cutting-edge components, including clean energy conversion, adaptable battery energy storage, clever traction power, and available energy management. It is made explicitly for non- or partially electrified lines and allows for efficient, environmentally friendly train operation while maintaining high-performance standards (Alstom 2022). Along with Alstom, Siemens Mobility has developed a hydrogen-powered passenger train and mobile hydrogen storage trailer. According to Siemens, testing of their train will start in the middle of 2023, and full service in Germany is planned to begin in January 2024 (IEA 2022a).

All over the world, interest in this technology is rising. Other countries are conducting their trials. When electrification is difficult, or the distances are too great for battery-powered trains to travel, hydrogen offers a way to reduce the carbon footprint of diesel rail lines. Hydrogen consumption for rail in 2021 was less than 0.1 kt due to the limited deployment of hydrogen in the railway sector. According to announcements from the industry, hydrogen's use in rail transportation is anticipated to increase soon (IEA 2022a).

Air and Maritime Transport

Even though the technologies are less developed than those for road and rail transport, interest in using hydrogen and synthetic fuels derived from hydrogen is also rising in the maritime and aviation sectors. In the next ten years, several projects for vessels that can run on hydrogen, ammonia, and methanol will become a reality. Several companies are also working on hydrogen-fueled aircraft, including Airbus, though commercialization will likely happen after 2030. Similar to this, it is not anticipated that the use of synthetic fuels derived from hydrogen will gain ground anytime soon (IEA 2022a).

The two main areas of activity that will drive demand for hydrogen in aviation are the production of hydrogen-derived sustainable aviation fuel (SAF) and the development of hydrogen-powered aircraft for short- to medium-haul flights. The cost is the main deterrent to deployment for both, but hydrogen-derived SAFs are much more developed. Aviation powered by hydrogen presents more technical challenges, and the field is still in an early stage (IEA 2022a).

2.5.3 Building Sector

Even though hydrogen can be used in fuel cells to generate heat and power with high efficiency, it can also be burned in boilers or combined heat and power (CHP) units to produce heat and power. Most of the hydrogen used in the energy sector still revolves around these methods. Most of this is completed on-site, where hydrogen is produced as a by-product of other processes (Fuel Cells and Hydrogen Observatory 2022).

Hydrogen plays a minimal role in the building sector (Meyer, Herkel, and Kost Sep. 2021). Almost one-fourth of all energy consumed worldwide in the building sector is used in natural gas-based heating and cooking technologies. Several countries are enacting bans on using fossil fuels in new construction, including France in 2022 and Austria in 2023, in response to the current energy crisis and national commitments to achieve zero emissions (IEA 2022a).

In buildings where natural gas infrastructure is already present and where it is difficult to decarbonize energy use, such as in cold climates, old city centers, and inadequately insulated structures, there may be opportunities for hydrogen applications. Networks for natural gas can be set up for hydrogen blending. The use of both new and old boilers and cookstoves may be impacted by increasing hydrogen blending ratios (Pedersen et al. 2022). Although there are already boilers that can blend hydrogen, equipment standards are developing to ensure that all boilers can operate safely at different hydrogen blending ratios (IEA 2022a). The development of the hydrogen economy is not seen as being driven by the building sector (Prognos, Öko-Institut, and Wuppertal-Institut 2020).

2.5.4 Electricity Generation

As a fuel, hydrogen plays a minor role in the power sector. Since converting hydrogen into electricity is frequently viewed as unfavorable from an economic perspective and is not competitive with the low costs of electricity and gas, it makes up less than 0.2% of the world's electricity production (Welder, Stenzel, et al. 2019). This could change in the future due to the massive increase in electricity prices resulting from the energy crisis and the rise of the market share of renewable energy, leading to a demand of more than 100 TWh by 2050 (Nitsch 2021).

Hydrogen-based electricity generation technologies are currently on the market. It is technically possible for some current designs of reciprocating gas engines, fuel cells, and gas turbines to run on hydrogen-rich gases or even pure hydrogen. Reciprocating gas engines can handle gases with a volumetric hydrogen content of up to 70%. Many manufacturers have shown off 100% hydrogen engines, which should be offered for purchase in the upcoming years (IEA 2022a).

Fuel cells can convert hydrogen into electricity and heat with up to 50–60% electrical efficiency. They continue to operate at high efficiencies even when partially loaded, which makes them especially attractive for supplying flexibility to electrical systems. The capacity of stationary fuel cells increased by 348 MW globally in 2021. Even though not all may be in use, and only about 90 MW use hydrogen as fuel, most stationary fuel cells still run on natural gas. The total installed capacity of stationary fuel cells worldwide in 2021 was about 2.5 GW (IEA 2022a).

Although there has not been much hydrogen deployed in the power sector yet, interest in using hydrogen and ammonia is growing. In the short term, co-firing with hydrogen or ammonia can lower emissions in current coal- and gas-fired power plants. Long-term flexibility or large-scale seasonal storage offered by hydrogen and ammonia-fired power plants can aid in integrating variable renewable energy sources.

2.6 Hydrogen and Energy Transition

2.6.1 Hydrogen Trade

The energy transition may include significant hydrogen trade on a global scale. In order to aid in the decarbonization of the energy system, there is an increasing demand for low-emission hydrogen and fuels derived from hydrogen worldwide.

Large-scale, specialized facilities for renewable energy generation can produce hydrogen, which can then be transported to demand centers. According to this model, large-scale wind and solar farms could be built, as well as other renewable energy sources like hydropower and geothermal energy, when appropriate, allowing for lower electricity production costs where the resource potential exists (IRENA 2019).

Through the diversification of fuels and supply sources, hydrogen imports may also help with concerns about energy security. Some countries want to significantly increase the use of low-emission hydrogen to decarbonize sectors like industry. However, they lack the domestic production capacity to do so at an affordable price. Other countries with low domestic hydrogen demand have plenty of renewable energy resources that can generate electrolytic hydrogen or the ability to generate fossil fuel-based hydrogen using CCS (IEA 2022a). A continent-wide or even intercontinental hydrogen market could result from this, bringing together countries with high levels of renewable energy potential and, consequently, export capacities (such as Australia, Chile, the Middle East & North Africa (MENA) Region, the Gulf Region) (Agora Energiewende und Wuppertal Institut 2019) and countries with high levels of hydrogen demand but less affordable or limited renewable energy potential like Germany (BMWi 2020).

The global market for hydrogen and associated shipping can be compared to natural gas, and hydrogen will likely need to be transported over significant distances. It requires more space than fossil fuel alternatives but is easier to transport due to its low volumetric density and relatively high energy content. With the cost of energy losses, hydrogen can be either compressed or liquefied, or it can be incorporated into energy carriers like ammonia, methanol, and other liquid organic hydrogen carriers to get around this characteristic (IRENA 2019). Different hydrogen transport and shipping methods were mentioned in Section 2.3.

2.6.2 Hydrogen Policies

Government intervention is necessary for adopting hydrogen as a new energy vector to proceed at the rate necessary to support global climate goals. In order to support hydrogen's role in the transition to clean energy and to achieve the goal of GHG emissions neutrality in 2050, governments are already collaborating with a range of stakeholders to identify effective policies. A country's priorities and limitations, such as the availability of resources and the state of the infrastructure, must be considered when designing policy instruments. There are numerous available policy options. Some key areas were outlined in the Future of Hydrogen report issued by the International Energy Agency (IEA) (IEA 2019) as recommendation points to scale-up hydrogen:

- Confidence should be given to stakeholders that there will be a future market for hydrogen by setting targets and long-term policies to create a vision for the role of hydrogen in the overall energy policy framework.

- The market's demand for clean hydrogen should be boosted. Although there are clean hydrogen technologies, costs are still a problem. Policies that create sustainable markets for clean hydrogen are required to support investments made by suppliers, distributors, and users.

- First-movers' investment risks should be identified. New applications for hydrogen and clean hydrogen supply and infrastructure projects are at the riskiest point of the deployment curve. Loans, guarantees, and other tools with specific objectives and time restrictions can support private sector investment, learning, and risk sharing.

- Research and development (R&D) should be encouraged to reduce costs. R&D is essential to lowering costs and improving performance, including fuel cells, hydrogen-based fuels, and electrolyzers.

- Harmonized standards should be set and regulatory barriers removed. Regulations and permit requirements, which are ambiguous, unsuitable, or inconsistent across sectors and countries, present challenges to project developers.

- Global development should be monitored. In all areas, improved international cooperation is required, but it is vital for standards, the sharing of best practices, and cross-border infrastructure.

In order to set policies and guidelines for hydrogen in the European Union (EU), the European Commission released its hydrogen strategy in 2020, which aims to make the EU carbon neutral by 2050. This strategy entitles installing 6 GW of electrolysis capacity by 2024, producing up to 1 Mt of green hydrogen. The electrolysis capacities should be increased to 40 GW by 2030, producing 10 Mt of green hydrogen (European Commission July 2020). In order to steer the EU towards long-term GHG neutrality, it is also emphasized that hydrogen must be produced sustainably using wind and solar energy. The EU Commission will invest 220 to 340 billion euros until 2030 to expand solar and wind energy facilities to guarantee enough electricity from clean, renewable sources (Erbach and Jensen April 2021).

Chapter 3

Methodology

In this chapter, an overview of the methodological approaches used in this thesis to disaggregate hydrogen demand into arbitrary regional aggregations is given. It is divided into three main sections. Firstly in section 3.1, an improved methodology for hydrogen demand in the industrial sector is presented. In section 3.2, two methods used for the transport sector are discussed. A brief explanation of the assumptions made in this thesis is presented in section 3.3. Finally, in the last part of this chapter, a developed tool written in the programming language Python to disaggregate the overall hydrogen demand across Europe in all considered sectors is presented in Section 3.4. The tool is developed to comprise all major hydrogen sinks like industrial production, transport, and heat sectors, etc. Hydrogen demands from studies, usually reported as national demand, are properly disaggregated using the tool to produce input for energy system models. This tool is introduced as regionalization tool (RegTool) in this thesis. When referring to Europe in the analysis, it means the European Union (EU27), without Malta and Cyprus, including the United Kingdom, Norway, Switzerland, Albania, Bosnia and Herzegovina, Serbia, and North Macedonia.

3.1 Industrial Sector

As illustrated in Figure 3.1, our method depends on the process-specific values of energy-intensive industries to calculate the hydrogen demand per plant. Assuming that the primary process related to these industries is switched to hydrogen, these values depend on the respective specific energy consumption of the process. They are related to the production output (unit: kg_{H2}/t). This unit is further converted to (TWh/t) using the lower heating value of hydrogen (unit: kWh/kg_{H2}). Steel, ammonia plants, and refineries, being considered energy-intensive industries, will be covered in this analysis.

Based on a comprehensive literature review, a database of industrial plants in the covered subsectors was developed. This database contains information about the plants, such as the facility's name, the type of industrial subsector, the starting year of operation, the address, and the annual production capacity. To construct this database, several individual datasets were combined as follows. The term subsector is used further in the thesis to describe the subdivisions of the industrial sector,

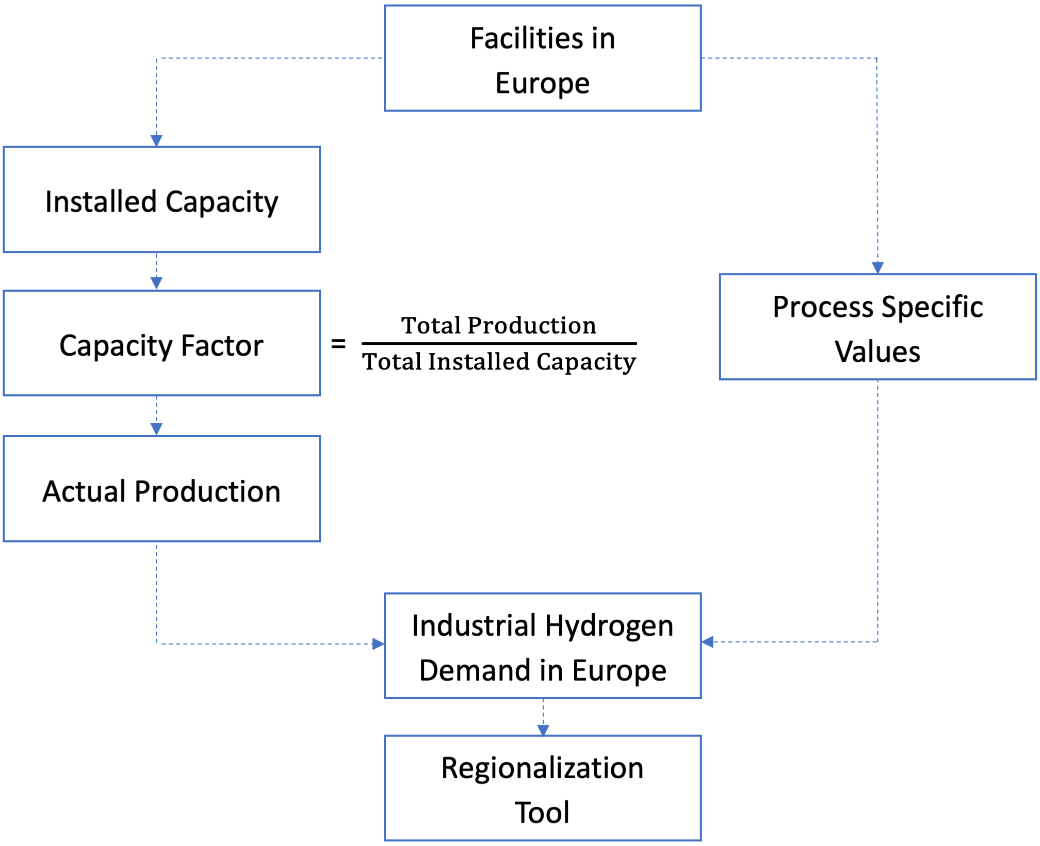

Figure 3.1 Overview of the modified methodology for the industrial sector

for example, steel, ammonia plants, and refineries.

3.1.1 Steel Plants

Information about the steel plants was retrieved from the European Steel Association (Eurofer) (European Steel Association 2021) and Global Energy Monitor (GEM) (Global Energy Monitor 2022) for the steel industry. As the steel manufacturers only report the annual capacity factor of the plant and not the actual annual production, a capacity factor had to be calculated to check each country's actual production. The capacity factor is defined as the actual production of a plant during an interval of time divided by the maximum capacity this plant can produce during the same interval of time. In our case, the capacity factor for each country is calculated based on the average production of that country between the years 2016 and 2020 and its aggregated steel production capacity. The calculated capacity factor is assumed to be constant within each country. The annual production for each of the plants included in the database is calculated based on the assumed capacity factor of the country and the plant's annual capacity. Finally, to check the reliability of the data, the estimated annual production of plants within the same country is aggregated and checked against the published report by the World Steel Association (World Steel Association 2021), which includes the aggregated actual annual steel production per country and is used as a reference containing real-world production capacities.

In this thesis, steel production volumes in 2050 are assumed to remain constant compared to the average production of the year between 2016 and 2020. This is done to mitigate the effect of the decrease in production caused by the pandemic in 2020. The institute of energy economics at the University of Cologne (Energiewirtschaftliches Institut an der Universität zu Köln 2021) used a similar approach and assumed constant steel production volumes in Germany until 2045. BF-BOF and DR-EAF steel plants are included in this analysis since both possess a conversion path to a hydrogen-based process.

3.1.2 Refineries

For refineries, data about the location and production capacity are retrieved from an existing dataset (Concawe 2021). Concawe is a division of the European Fuel Manufacturers Association. It was founded in 1963 by a small group of major oil companies and now includes most oil companies operating in Europe. Concawe has observer status at the United Nations Economic Council for Europe (UNECE).

Due to the lack of other datasets and data about the actual production, an assumption is made that the refineries were working with a capacity of 80%, and checking the reliability of data against other sources is not possible for this subsector. Like steel plants, production volumes of refineries are assumed to remain constant at their rates in 2021 by 2050. The data are checked manually to ensure their accuracy. This is done by comparing the values from Concawe's dataset with plants' websites.

3.1.3 Ammonia Plants

A plant-by-plant approach was executed for ammonia plants due to the lack of databases for this subsector. Internet research for individual companies in the EU for ammonia plants was done to gather the plants' production capacity and coordinates. A facility capacity factor of 80% was assumed for ammonia plants. Similarly, production volumes of ammonia plants in 2050 are assumed to remain constant compared to the values of 2020.

Table 3.1 summarizes the data sources used to generate the industrial sites' database.

Subsector	Source of data	Extracted data
Steel	Global Energy Monitor (GEM)	Coordinates, and production capacity
Chemical/ Ammonia	Internet research for individual companies	Coordinates, and production capacity
Refineries	Concawe 2021	Coordinates, and production capacity
All Subsectors	Individual plants' websites	Coordinates, and production capacity

Table 3.1 Overview of used datasets for the industrial sector

3.2 Transport Sector

Coming up with different methodologies than the industrial sector was necessary to disaggregate the hydrogen demand for the transport sector. Two methodologies will be presented, one for road transport and the other for air transport. This is done as it is not possible to allocate the hydrogen demand for road transport in a single point compared to the industrial facilities that can be used as fixed-point sources to which you can allocate the hydrogen demand.

3.2.1 Road Transport

The main challenge for road transport is the lack of point sources to which you can allocate the hydrogen demand to compared to the industrial facilities, which always have a fixed location of consumption. Therefore, a different methodology is derived to disaggregate this subsector's hydrogen demand (as shown in Figure 3.2).

Firstly, the average hydrogen consumption per vehicle is calculated. The vehicles covered in this analysis include cars, buses, lorries, and road tractors. This is achieved by dividing the average tank size of each type of vehicle in (kg) by the average operating range in (km). To calculate the average traveled distance of each vehicle in a year, the road traffic for each type of vehicle in (Million Vehicle km) in a country reported by Eurostats (Eurostat 2021c) is divided by the total number of each type of vehicle within the same country. In case of the lack of reported data for some countries, it is assumed that the average traveled distance of a particular type of vehicle would equal the value of another country having almost the same area and population. The annual hydrogen demand per vehicle of each type of vehicle within a country is calculated by multiplying the calculated average hydrogen consumption by the yearly average traveled distance of the same type of vehicle.
After calculating the annual hydrogen demand per vehicle within a country, it is necessary to figure out the total annual demand for all vehicles per region. The number of registered vehicles per type per NUTS 2 region is reported by Eurostats (Eurostat 2021d). This data is disaggregated to the local administrative units (LAUs) by share of the population. Finally, the total hydrogen demand for each type of vehicle within an LAU is calculated by multiplying the total number of vehicles by the hydrogen demand per vehicle.

Market penetration measures how much a product is sold relative to the total estimated market for that product. (Cerniauskas et al. 2019) review scenarios to analyze the relevant hydrogen vehicles' market penetration and growth rates for the years between 2023 and 2050. The scenarios are focused on Germany; however, relevant European scenarios are also considered. Different market penetration scenarios are taken into account in their analysis.

To allocate the hydrogen demand, LAUs are used as point sources. A script was developed to fetch the latitude and longitude of each LAU. The fetched geocoded point is generally at the center of the LAU. This ensures the flexibility to use any customized shapefile for the road transport sector in the regionalization tool.

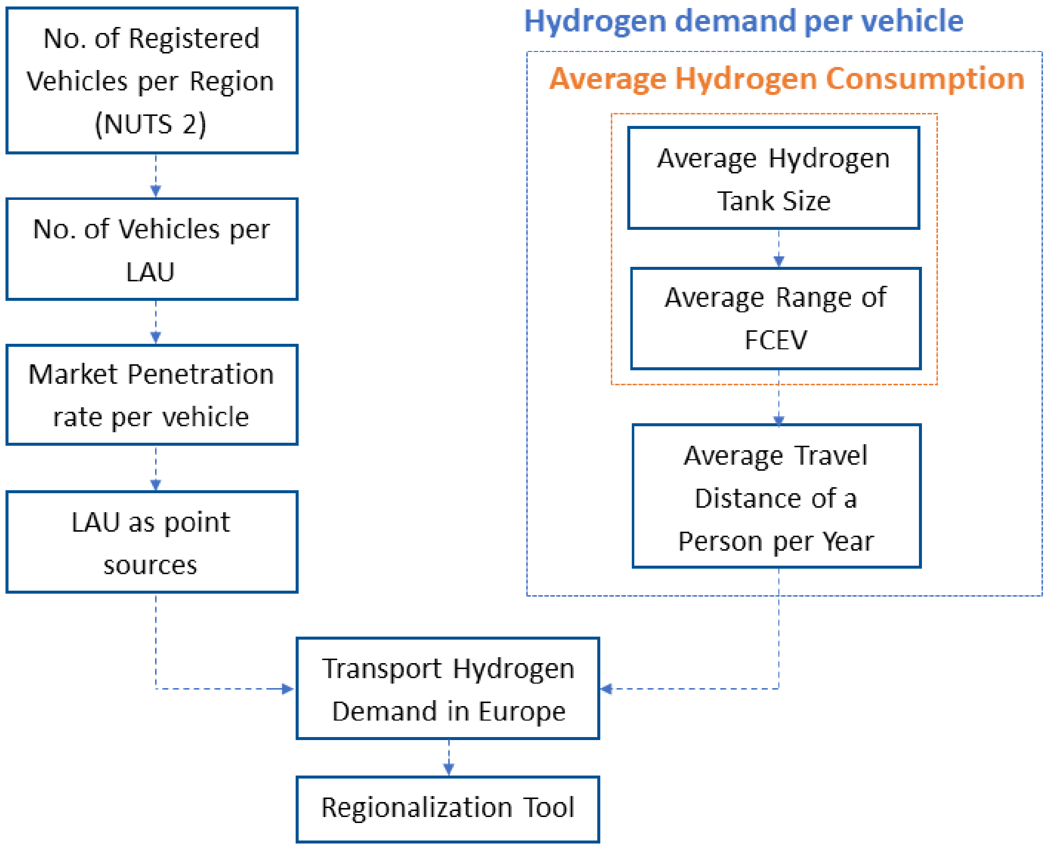

Figure 3.2 Overview of the methodology to disaggregate the hydrogen demand for the road transport subsector

3.2.2 Aviation

The hydrogen demand for each airport is modeled and forecasted as part of the Development pathways for Aviation up to 2050 (DEPA 2050) project published by the Institute of Air Transport and Airport Research and the German Aerospace Center (DLR) (Leipold et al. 2021). The project's first step involved conducting in-depth system and trend analyses of the aviation market, technologies, alternative fuels, maintenance, and air traffic management. A subsequent impact analysis of the long-term effects could be conducted with particular consideration for the overall objective of making the aviation industry climate-neutral by 2050 when combined with vehicle-specific demand forecasts for future passenger and flight growth. Significant technological potential emerged in this area, but more steps are required to achieve overall climate neutrality. The total CO_2 emissions are likely to rise by 2050 due to the predicted increase in global air traffic, even though the relative CO_2 emissions per passenger-kilometer decreased in all investigated scenarios. Additional technological developments and a rise in the use of environmentally friendly aviation fuels are required to offset the corresponding negative impact.

The data is modeled under the following assumption:

- Only passenger traffic and scheduled services are considered
- Traffic forecast includes the pandemic impact
- Hydrogen aircraft are used for short, medium, and regional flights
- All routes that hydrogen aircraft cannot fly due to range are flown by conventional aircraft

3.3 Assumptions

An important assumption is made for the industrial and transport sectors. For the industrial sector, it is assumed that the currently existing facilities would remain in operation until 2050 without considering the new facilities entering into operation. Thus, the industrial facilities database needs to be regularly updated in the future to get accurate results.

It was also assumed that the total number of vehicles would not change for the transport sector. Instead, hydrogen-operated vehicles will replace some of the existing conventional vehicles with a specific market penetration rate. Thus, regular updates to the transport database are necessary in the future. This corresponds to a report about automotive revolution in 2030 published by McKinsey & Company (Gao et al. 2016) that estimates a fall in the annual growth rate of the overall global car sales from 3.6% over the last five years to around 2% by 2030. This drop will be largely driven by the rise of new mobility services such as car sharing.

3.4 Regionalization Tool (RegTool)

The methods introduced above are combined into a single application that allows disaggregating an overall hydrogen demand of, for example, the continent to an arbitrary aggregation of regions in Europe.

In this thesis, the disaggregation of hydrogen demand across Europe for the industrial and transport sector is the focus. The work in the industrial sector is partly based on data collected in a previous master's thesis (Wittenberg 2021). The collected data on locations and hydrogen demand of the point sources is collected and prepared in a file, which serves as input into the tool.

The most crucial feature of the tool is flexibility with regard to regional aggregation. Instead of having the inputted shapefile hard-coded into the tool, the users should be able to select the shapefile they want to disaggregate the demand to without going through the script and pasting the path to their shapefile into the code. For this purpose, a function was added to the tool, opening a file dialogue and asking the user to select his desired shapefile.

RegTool is generalized to use a customized or a standard shapefile as input. The NUTS classification is an example of standardized shapefiles (Eurostat 2021b) used with this tool. It is the European Union's division into EU regions, NUTS 0 being the countries' borders, NUTS 1 contains 92 major socio-economic regions, NUTS 2 covers 242 basic regions for the application of regional policies, and NUTS 3, having the highest resolution, lists 1,166 small regions for specific diagnoses.

For local statistics, Eurostat maintains a system of Local Administrative Units (LAUs) (Eurostat 2021a) compatible with NUTS. The LAUs represent the municipal and commune units of the European Union, which make up the NUTS. At the same time, the customized shapefile designed for the research project "Roadmap Gas Transition" (DLR 2021) was chosen to test the tool against the customized shape-files.

One of the qualities considered in the tool is its sustainability and the ability to maintain it in the future to ensure easy updates. For this purpose, a database was created in an excel file, providing more accessible future data updates. A graphical user interface (GUI) (as shown in Figure 3.3) was designed to make the tool user-friendlier. The user can input the future estimated hydrogen demand and select the desired shapefile to which they want to disaggregate the hydrogen demand.

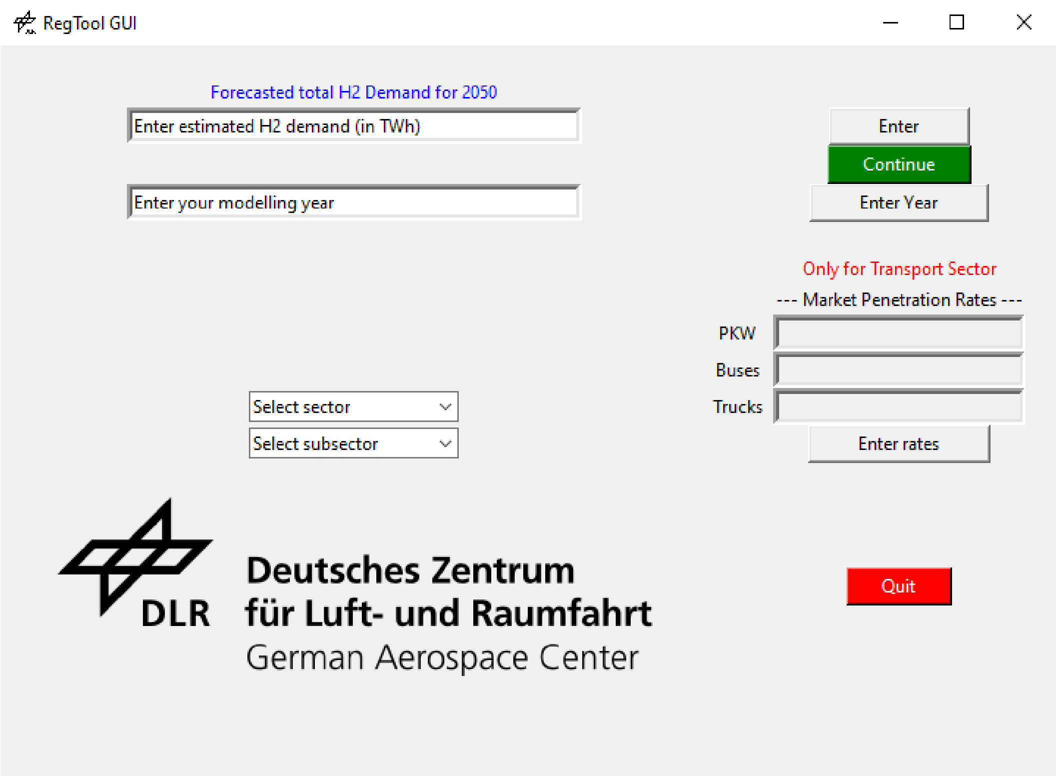

Figure 3.3 Regionalization tool's GUI

Another feature of the tool is giving the user a choice whether to regionalize the overall hydrogen demand or only specific sectors. The user can visualize the disaggregated hydrogen demand per sector, for example, for the industrial or transport sector or even for subsectors, for instance, refineries, steel or ammonia plants within the industrial sectors or road transport,or aviation within the transport sector.

This will give the user more insights into the future hydrogen demand within each region, like the nature of the demand and the distribution of the demand between different subsectors within a region. In addition, data about hydrogen demand for a specific sector is only reported in studies. Thus, this makes it easier to use the tool and disaggregate the demand.

The disaggregated hydrogen demand is visualized on an interactive map which can be accessed from an HTML file. For the industrial sector, markers represent the exact location of different industrial facilities. By clicking on one of them, more data about this facility can be accessed, like the starting year of operation, the subsector type, the address, and the hydrogen demand of this facility (as shown in Figure 3.4). Two choropleth layers are used, one to visualize the current hydrogen demand and the other one for future demand in 2050. The choropleth layers and the markers can be hidden or shown according to the user's preference.

Figure 3.4 Plant information displayed in the tool

Chapter 4

Results

The outcomes of applying the methods described in Chapter 3 are presented in this chapter. The findings of a review of studies that focus on the forecasted hydrogen demand in Europe are presented in Section 4.1. The regionalization tool's findings for the industrial sector, as well as the data used behind the tool, are presented in Section 4.2, while those for the transport sector are presented in Section 4.3.

The regionalization tool developed as part of this thesis aims to give an overview of the distribution of hydrogen demand. The input is the demand for hydrogen, which is then distributed accordingly. The output will include information on the spatial distribution, the modeling year, the sector and subsector being considered, its additional details, and the resulting value of hydrogen demand in TWh.

4.1 Forecasted Hydrogen Demand

An overview of a couple of studies and reports forecasting the future hydrogen demand in Europe for the industrial and transport sectors between 2030 and 2050 is presented in this section. The values extracted from these reports will be used later as the input to the regionalization tool, which will be disaggregated over different European regions.

4.1.1 Hydrogen council and McKinsey & Company (2021)

In terms of clean hydrogen, this report predicts a total hydrogen demand of 95 Mt across all sectors in Europe as it possesses a robust industry-wide decarbonization momentum. In order to achieve the climate goals for feedstock, industrial energy, mobility, and power, hydrogen should play a significant role. The demand for clean hydrogen in Europe is anticipated to scale up proportionately earlier than in other regions worldwide and will be partially met by imports (McKinsey and Company, Hydrogen Council 2021). The distribution of this demand along different sectors is illustrated in Figure 4.1. It could be noticed that the demand for the transport sector will exceed the industrial one in 2050. This might be due to the direct and indirect electrification of this sector.

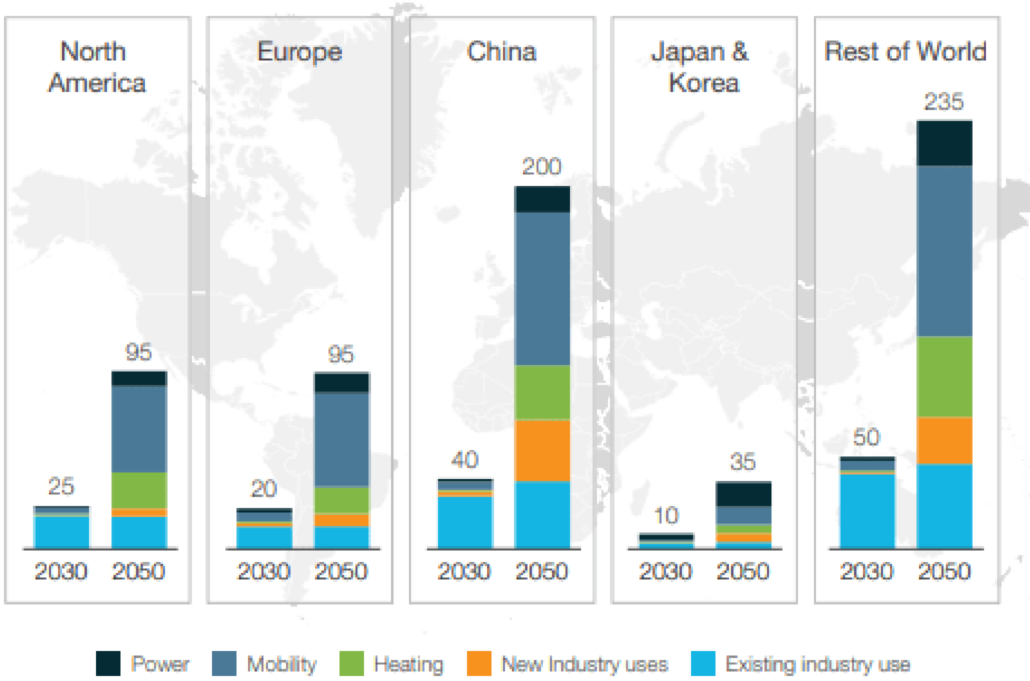

Figure 4.1 Hydrogen demand per region in (Mt) (McKinsey and Company, Hydrogen Council 2021)

4.1.2 Agora Energiewende and AFRY Management Consulting (2021)

This study examines the potential hydrogen demand needed to decarbonize specific industrial sectors. In the chemical industry, approximately 6.4 MWh of hydrogen is required to produce one tonne of ammonia. As a result of the 15 Mt ammonia demand expected by 2050, 96 TWh of hydrogen is needed. A transition is expected from mineral naphtha toward imported sustainable naphtha between 2020 and 2050, as well as non-oil-based transport fuels. These projections predict a prolonged decline in hydrogen demand in refineries between 2020 and 2030, an increase between 2030 and 2040, a slowdown after 2040, and a final decline to zero in 2050. As for the steel industry, this study assumes that existing blast furnace plants in Europe will be converted to use the DRI process. According to this assumption, the proportion of DRI plants will reach 34% by 2030, 87% by 2040, and 100% by 2050. By 2050, it is predicted that the steel industry will have a total hydrogen demand of 123 TWh. This is the most significant sectoral increase in hydrogen demand considered in this study (Agora Energiewende and AFRY Management 2021). Figure 4.2 illustrates Europe's forecasted industrial hydrogen demand for the next decades per subsector.

4.1.3 GRTgas (2021)

According to this study (Wang et al. 2021), the demand for hydrogen in the steel industry is projected to be 55 TWh/year by 2030 and nearly triple to 143 TWh/year by 2040. Europe's fully decarbonized steel sector is expected to have a 179 TWh/year

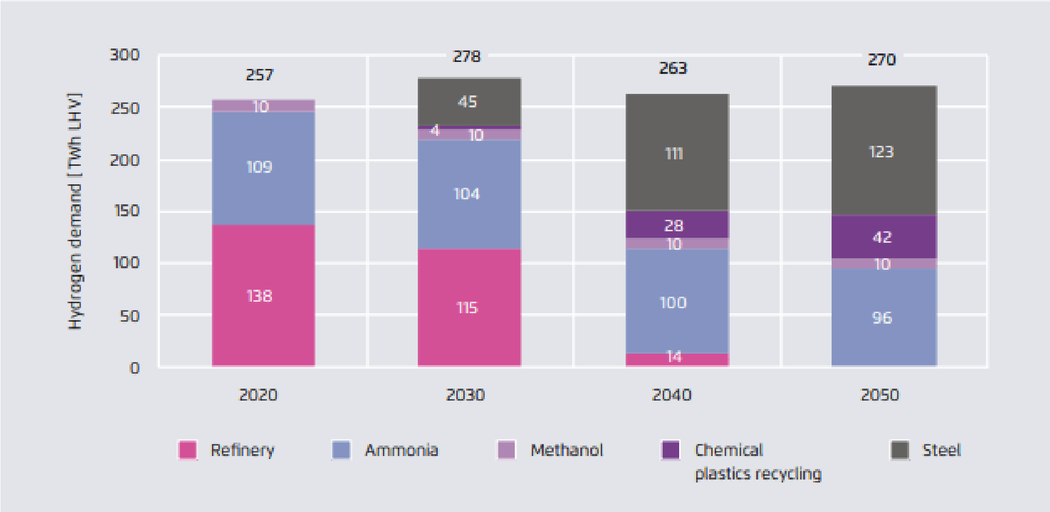

Figure 4.2 Forecasted industrial hydrogen demand (Agora Energiewende and AFRY Management 2021)

hydrogen demand by 2050. Ammonia production is expected to remain constant, with a hydrogen demand of 113 TWh/year. In the short term, the current production of grey hydrogen will gradually be replaced with blue hydrogen. In contrast, green hydrogen and biomethane will play a more significant role mid-to-long term. The demand for green and blue hydrogen is anticipated to be 7 TWh/year in 2030, 53 TWh/year in 2040, and 113 TWh/year in 2050. The hydrogen demand in refineries is expected to reach 175 TWh by 2030, 495 TWh by 2040, and 691 TWh by 2050. In this study, the demand for hydrogen from fuel production includes upgrading to biokerosene, synthetic kerosene, and fuels for FCEVs, as well as hydrogenation of fossil fuels.

Moreover, the same study considers hydrogen a viable option for decarbonizing heavy-duty road transportation, particularly for long-distance vehicles. In 2030, 2040, and 2050, respectively, hydrogen fuel cells are expected to power 5%, 30%, and 55% of trucks and 4%, 21%, and 25% of buses. In 2030, 2040, and 2050, respectively, Europe's predicted demand for direct hydrogen in heavy road transport is 21 TWh, 131 TWh, and 217 TWh, or 3%, 25%, and 58% of the total energy demand for heavy road transport, respectively. In order to decarbonize aviation, hydrogen, and fuels derived from hydrogen are identified as promising alternatives. In Europe, the demand for direct hydrogen in aviation is anticipated to be 0 TWh, 9 TWh, and 68 TWh, respectively, representing 0%, 1%, and 9% of the total aviation energy demand in the years 2030, 2040, and 2050 (Wang et al. 2021).

Table 4.1 summarizes the forecasted values (in TWh) for the aggregated hydrogen demand in Europe for different sectors and subsectors that will be used as input in the regionalization tool.

Subsector	2030	2040	2050
Chemical/ Ammonia	113	113	113
Steel Industry	55	143	179
Refineries	175	495	691
Road Transport	21	131	217
Air Transport	0	9	68

Table 4.1 Forecasted hydrogen demand (in TWh) in Europe per subsector

4.2 Industrial Sector

The industrial hydrogen demand in Europe is estimated using the gathered information on production sites and process-specific hydrogen demand. To the author's knowledge, 134 steel plants, 19 ammonia production plants, and 93 refineries are operating in the considered region illustrated in Figure 4.3. The dots represent the exact location of each of the facilities. In Germany, known as the industrial hub of Europe, which is confirmed by the analysis of the production sites, 4 ammonia sites, 15 refineries, and 22 steel plants are located. The shapefile further used in the analysis is a customized shapefile designed for the DLR research project "Roadmap Gas Transition" (DLR 2021).

Table 4.2 summarizes the specific hydrogen demand per considered processes to calculate the demand for refineries, steel, and ammonia production sites.

Process	Specific Value (kg_{H2}/t)
Steel	20.2
Ammonia Production	175
Refinery - Hydrocracking	27
Refinery - Catalytic Cracking	7.2
Refinery - Hydration of Cokers	4.5

Table 4.2 Specific hydrogen demand of industrial processes in (kg_{H2}/t) (derived from (Welder, Ryberg, et al. 2018))

4.2.1 Steel Plants

After the actual production of each steel plant is calculated using the method mentioned in Section 3.1.1, the data points within each country are aggregated and compared to the total production per country published by the World Steel Association (World Steel Association 2021). The top 5 countries with the most significant production steel capacities are summarized in Table 4.3. However, some key points about the data are interesting. For instance, the actual produced amount of steel for some countries exceeds the recorded total installed capacity. This was the case for Portugal and Albania. According to the World Steel Association, Portugal recorded a total steel production of 1,953 thousand tonnes in 2021, while only 1,700 thousand tonnes of annual production capacity were installed. In the case of Albania,

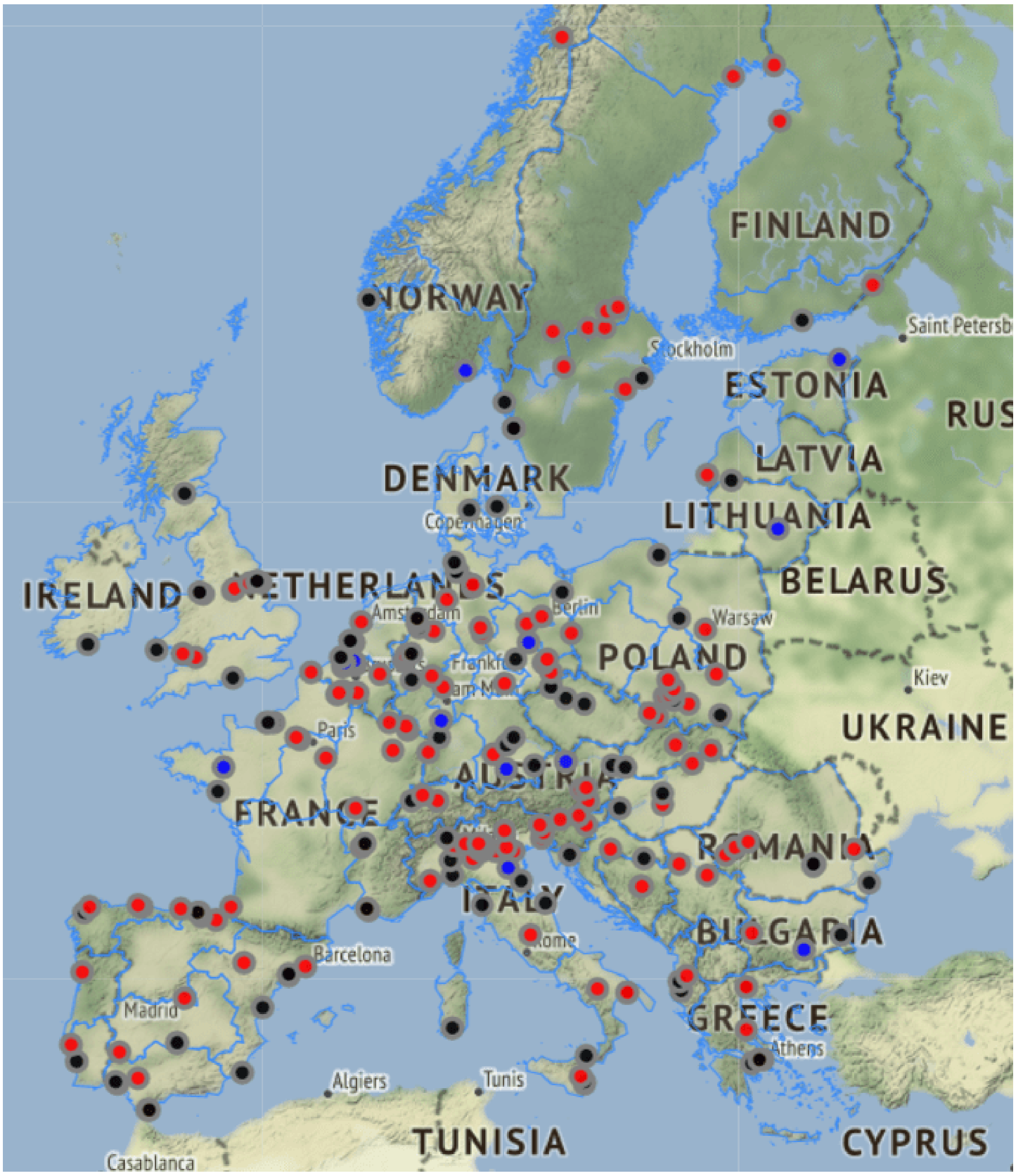

Figure 4.3 Location of ammonia plants, steel plants, and refineries in the considered region. Blue dots represent the ammonia production sites, red dots for steel plants, and black for refineries

the recorded production has been decreasing since 2014 until reaching zero in 2017, without any evidence of the decommissioning of the only plant in the country located in Elbasan.

Country	**Production capacity of crude steel (Thousand tonnes per year)**
Germany	49,750
Italy	34,225
Spain	18,340
France	17,600
United Kingdom	11,020

Table 4.3 Top 5 countries with the most significant crude steel production capacity in Europe (derived from (European Steel Association 2021))

The total forecasted hydrogen demand for the steel industry is expected to reach 179 TWh in 2050, according to the GRTgas report (Wang et al. 2021), which is considered the second-largest hydrogen-consuming sector in Europe in 2050 in their study. This value is disaggregated further by the regionalization tool rendering the demand map shown in Figure 4.4. The blue legend represents the disaggregated hydrogen demand per region, based on the process-specific methodology applied in this thesis, assuming a complete switch to green hydrogen and hydrogen-based alternatives at all the industrial sites included in the developed database. At the same time, the purple legend represents the disaggregation of the total forecasted hydrogen demand per sector in any specific year. The forecasted hydrogen demand is extracted from studies and reports. The most significant demand in Europe is in Germany, particularly in the North Rhein Westphalia region, with a 16.5 TWh demand which agrees with the findings of this study (Neuwirth et al. 2022). Moreover, Italy, being the second country in the production capacity of crude steel in Europe, presents a vast potential for the future hydrogen demand with 16.3 TWh demand in the northern part of Italy, where almost 80% of the steel plants in Italy are located and 10.3 TWh demand in the southern part where the ArcelorMittal BF-BOF plant with the most significant production capacity in the country is located. North Europe also presents a huge possible hydrogen demand, especially in the northern parts of Germany, Belgium, The Netherlands, and France, in addition to the central part of the United Kingdom and Austria, with an average demand of 8.5 TWh. The hydrogen demand values for the steel industry for all regions can be found in the appendix A.1.

4.2.2 Ammonia Plants

The ammonia industry is Europe's second largest hydrogen consumer nowadays (Fuel Cells and Hydrogen Observatory 2022). However, the production in this sector is expected to remain constant between 2030 and 2050, resulting in a hydrogen demand of 113 TWh/year (Wang et al. 2021). In other studies (McKinsey and Company, Hydrogen Council 2021), the demand is expected to decrease from 104 TWh in 2030 to 96 TWh in 2050. Following the first study and disaggregating the 113 TWh of hydrogen demand is illustrated in Figure 4.5.

The region with the major hydrogen demand for ammonia production is the Nether-

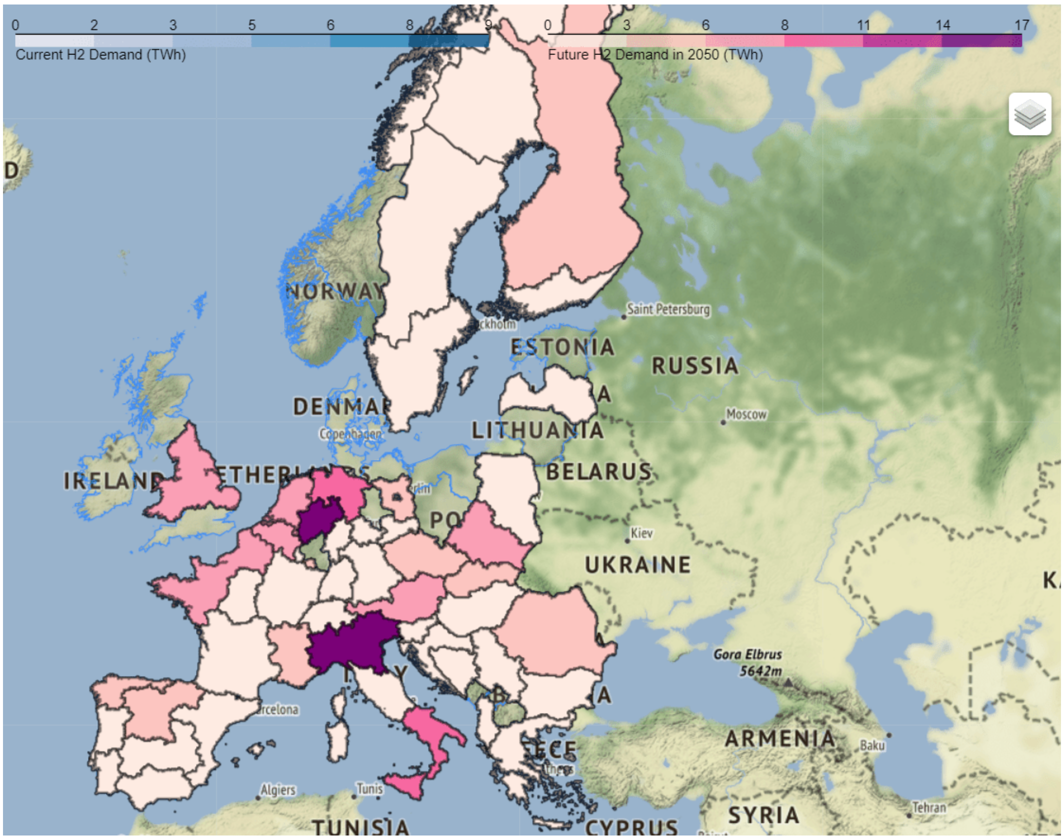

Figure 4.4 The disaggregated European hydrogen demand per region for the steel industry in 2050

lands, with a demand of 19 TWh. This is due to the fact that the plant with the most significant production capacity in Europe is located in Sluiskil in the Netherlands. This production site is owned by Yara, one of the biggest companies in the chemical industry. In Germany, four main production sites are located in four different federal states: Bayern, Saxon Anhalt, Rhineland-Palatinate, and Schleswig-Holstein. The one with the biggest production capacity is the one in Wittenberg, with an expected demand of 12 TWh. The demand for the other three sites varies between 4.9 and 8.8 TWh.

Moreover, the northern part of the French coast and Lithuania have an expected hydrogen demand of 9.5 TWh each. Other regions, such as the north of Italy, south of Norway, and Austria, require a varying hydrogen demand of between 5 and 6 TWh each. The hydrogen demand values for the ammonia production sites for all regions can be found in the appendix A.2.

4.2.3 Refineries

The refining industry represents the largest consumer of hydrogen in Europe (Fuel Cells and Hydrogen Observatory 2022). Studies forecast that the hydrogen demand for fuel production will be six times larger in 2050 compared to the current values, even though the demand for fossil fuels will fall sharply (IEA 2021b). How-

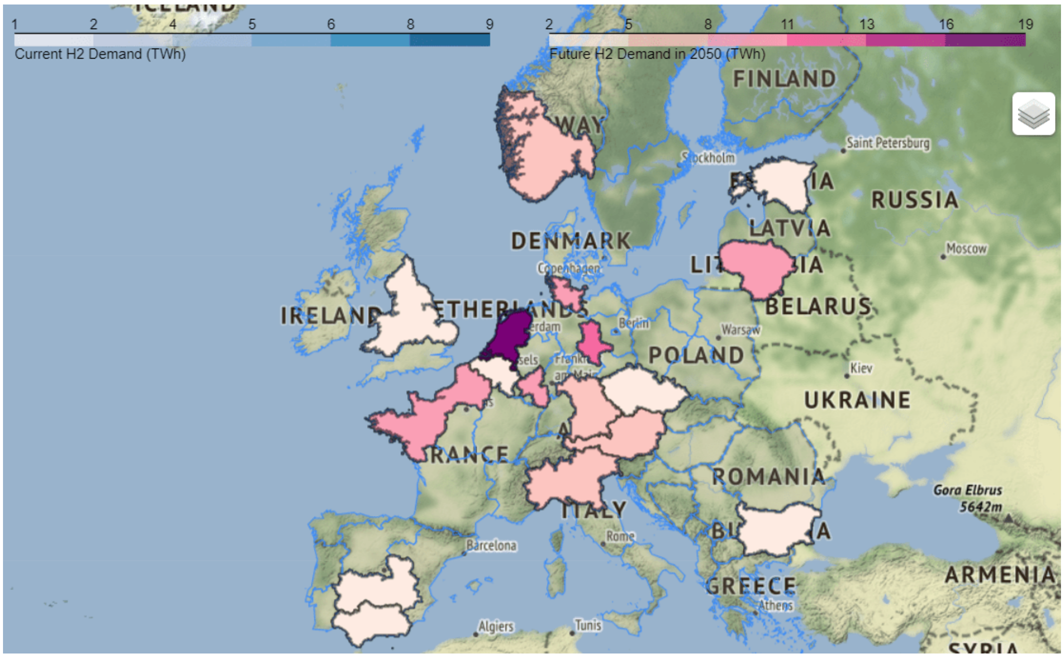

Figure 4.5 The disaggregated European hydrogen demand per region for the ammonia production sites in 2050

ever, the demand is expected to reach a value of 691 TWh, including the production of bio-kerosene, synthetic kerosene, fuels for FCEVs, and hydrogenation of fossil fuels (Wang et al. 2021).

The forecasted hydrogen demand for refineries is disaggregated over the considered regions and illustrated in Figure 4.6. The Netherlands, containing the biggest two refineries in Europe located in Rotterdam with capacities of 19.7 and 20.2 Mt/year, along with three other sites in the country, is expected to be the primary consumer for hydrogen in the refining sector with a demand of 63.8 TWh. The major refining sites are mainly located in coastal regions on the Mediterranean Sea, North Sea, Baltic Sea, or the English Channel, such as the southern part of Italy with an anticipated hydrogen demand of 44 TWh, Belgium with a demand of 34.75 TWh, northern and south-east coast of France with a demand of 36.4 and 23.4 TWh, respectively, the central region of the United Kingdom with a demand of 39.5 TWh. The hydrogen demand values for the refining subsector for all regions can be found in the appendix A.3.

4.2.4 Total Demand for the Industrial Sector

The profile distribution of the hydrogen demand for the industrial sector, consisting of steel plants, ammonia sites, and refineries, in Europe is mainly affected by the demand for refineries. The regions hosting the main future hydrogen demand are regions where refineries are located. This is illustrated in Figure 4.7, where the demand for the whole sector is presented and can be observed by comparing it to Figure 4.6. The appendix A.4 contains the industrial hydrogen demand values for all regions.

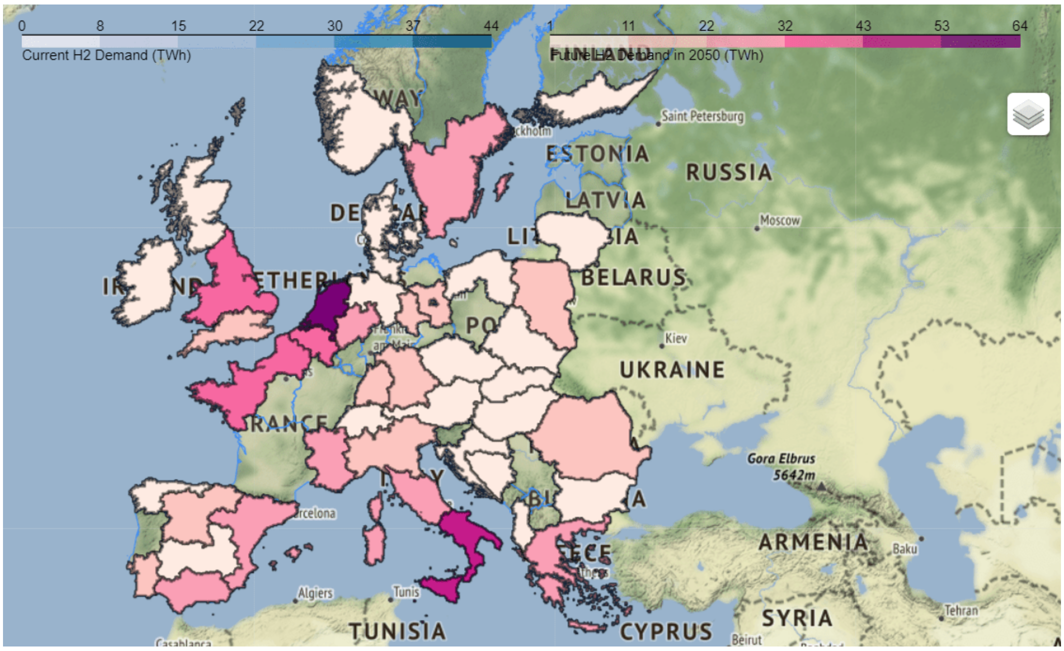

Figure 4.6 The disaggregated European hydrogen demand per region for the refineries sites in 2050

On a country scale, Germany, the biggest economy in Europe, will be the most considerable consumer of hydrogen for the industry in 2050, with a demand of 165.6 TWh, followed by Italy, with a demand of 114.7 TWh. Spain, The Netherlands, France, and the United Kingdom ranked between the third and the sixth places with demands of 89.8 TWh, 82.4 TWh, 79.4 TWh, and 68.9 TWh, respectively. Figure 4.8 compares the first six countries with the largest industrial hydrogen demand in Europe.

4.3 Transport Sector

4.3.1 Road Transport

The disaggregation of the hydrogen demand for road transport was challenging for many reasons. Firstly, there are no stationary point sources to which the demand could be allocated compared to the industrial sector, where the demand is allocated to the facilities. Secondly, many external effects affect the correct allocation of demand. On one side, the number of registered vehicles per region is used to calculate the hydrogen demand within the same region. On the other side, car-sharing vehicles are not sometimes driven in the same place they are registered. In addition, companies' vehicles are considered to be the same case as the one for car-sharing. Thus, further analysis is necessary before disaggregating the hydrogen demand to determine these factors' effects on the results of the regionalization tool.

Firstly, the effect of the existence of a car manufacturing company within a city on the number of registered private vehicles within the same city is investigated. For

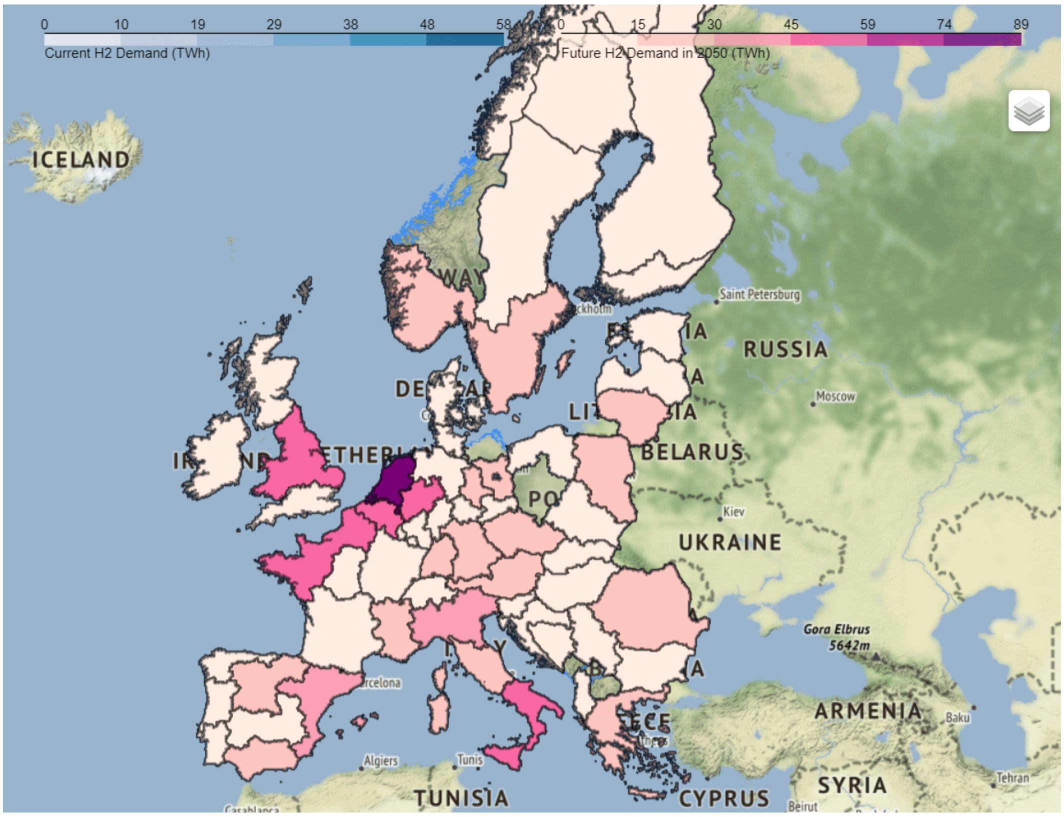

Figure 4.7 The disaggregated European hydrogen demand per region for the whole industrial sector in 2050

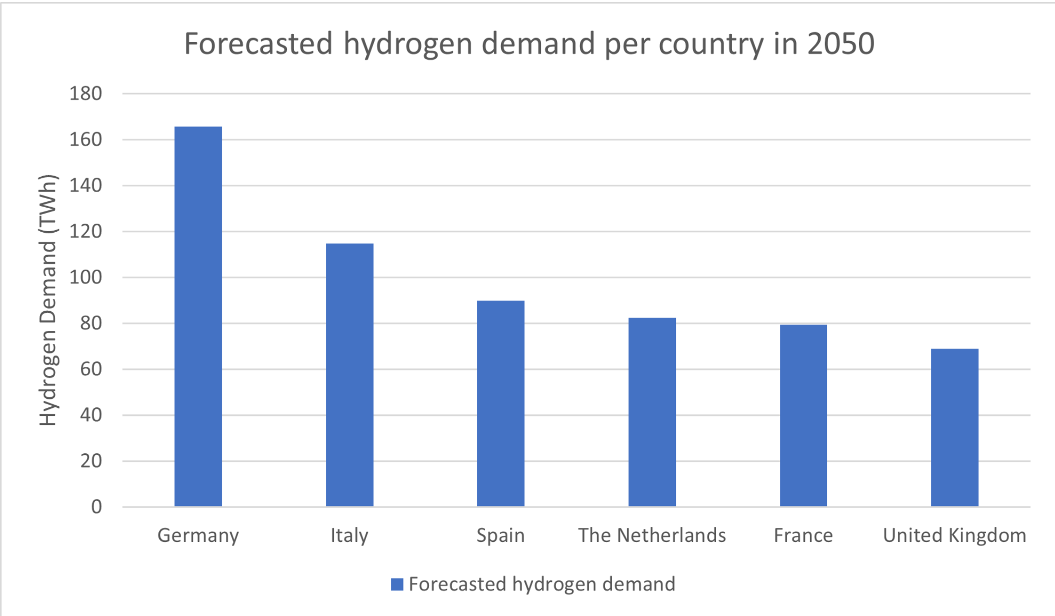

Figure 4.8 The disaggregated European hydrogen demand for the industrial sector per country in 2050

Analysis no.	City	Population	No. of registered vehicles
1	Wolfsburg	123,945	122,681
1	Nienburg (Weser)	121,854	79,166
2	Ingolstadt	138,016	98,857
2	Erding	139,622	91,412
3	Munich (Stadt + Landkreis)	1,911,813	982,528
3	Hamburg	1,852,478	810,489
4	Stuttgart	609,560	301,509
4	Dortmund	602,713	297,964

Table 4.4 The population and number of registered vehicles for the included cities in the analysis. The number of registered vehicles is derived from (Kraftfahrt-Bundesamt 2022), the population of cities in Bayern from (Bayerisches Landesamt für Statistik 2021), the population of Stuttgart from (Statistisches Amt der Landeshaupt Stuttgart 2022), the population of Hamburg from (Statistikamt Nord 2020), the population of Dortmund from (Dortmunder Statistik 2021), and cities in Niedersachsen state from (LANDESAMT FÜR STATISTIK NIEDERSACHSEN 2021)

this purpose, the number of registered private vehicles within two cities in Germany with close populations is compared. The cities included in the analysis are:

- Wolfsburg, where the headquarters of Volkswagen (VW) is located.
- Ingolstadt, where headquarter of Audi is located.
- Munich, where the headquarter of BMW is located.
- Stuttgart, where several companies are located, such as Mercedes-Benz and Porsche.

Table 4.4 summarizes the cities included in this analysis with the population and number of registered vehicles for each. The plots in Figure 4.9 illustrate the comparison between the cities.

In two of the four cities included in this analysis, companies' car affects the total number of vehicles registered within a specific region. In Wolfsburg, the number of registered private vehicles is 55% higher than in a city with the same population, such as Nienburg (Weser). Moreover, the number of registered private vehicles in Munich is almost 18% higher than in Hamburg. However, this effect can not be observed in the case of Stuttgart and Ingolstadt. To summarize, it is more about the location of the car group manufacturer's headquarters than the production plants. As there are only a few cities in Europe where the main headquarters of a car group manufacturer is located, thus this effect can be neglected.

Secondly, the effect of the number of car-sharing vehicles is investigated. The number of registered car-sharing vehicles in Germany in 2020 reached almost 26 thousand (Bundesverband CarSharing 2021), compared to 54 million private vehicles registered in Germany (Kraftfahrt-Bundesamt 2022). On a more local scale, the total number of private vehicles registered in Munich in 2019 reached almost

Figure 4.9 Comparison between the number of registered vehicles within cities with close populations

750 thousand (Kraftfahrt-Bundesamt 2022), and only 3,133 were car-sharing vehicles (Bundesverband CarSharing 2019). Thus, the number of car-sharing vehicles is too small and can be neglected.

Lastly, it is crucial to take into account the market growth rate of hydrogen in different applications in the transport sector. A scenario review of market diffusion from 2023 to 2050 for each hydrogen market was conducted to assess each hydrogen application's growth and utilization for the road transport subsector in this research paper (Cerniauskas et al. 2019). While Germany is the main focus of the scenario overview, relevant European or global scenarios were also considered when there was a lack of data. While some scenarios predict strong support of hydrogen adoption, others seem to anticipate that hydrogen will not play any roles in certain sectors. Therefore, low and medium adoption scenarios are considered in this analysis to disaggregation of the hydrogen demand in the road transport subsector. The penetration rate for each market by 2050 for both scenarios is presented in Table 4.5.

In 2050, Europe's forecasted hydrogen demand in road transport is expected to reach a value of 217 TWh accounting for 58% of the total heavy transport energy demand (Wang et al. 2021). In Figure 4.10, the disaggregation of this demand is illustrated. Compared to the medium market penetration scenario (Cerniauskas et

Scenario	Car	Bus	Truck
Low	0.25	0.3	0.25
Medium	0.5	0.6	0.5

Table 4.5 Hydrogen market penetration for each application by 2050

al. 2019), (Wang et al. 2021) study predicts that the hydrogen demand for private vehicles will be negligible and that the mentioned demand is only for buses and trucks. It also predicts that hydrogen fuel cells will power 25% and 55% of buses and trucks, respectively. In contrast, the medium scenario of (Cerniauskas et al. 2019) predicts a diffusion of hydrogen fuel cell technology in 50%, 60%, and 50% of cars, buses, and trucks, respectively. Thus, this is the main reason behind the difference between the calculated hydrogen demand in the blue legend and the disaggregated one in the purple legend.

The United Kingdom, with almost 32 million cars, 160 thousand buses, and 4.7 million trucks (Eurostat 2021d), is expected to become one of the largest hydrogen consumers in the road transport subsector with a demand of 16.7 TWh in the central part and 12 TWh in the southern part. This is followed by the northern part of Italy, where almost 47% of the population lives (I.Stat 2022), with a demand of 11.2 TWh. In Germany, as the number of vehicles in the western federal states exceeds the eastern one, the most significant three federal states in hydrogen consumption are Bavaria, North Rhine-Westphalia, and Baden-Württemberg with a demand of 6.8 TWh, 5.7 TWh, and 5.1 TWh, respectively. The hydrogen demand values for the road transport subsector for all regions can be found in the appendix A.5.

4.3.2 Aviation

The European hydrogen demand in aviation is forecasted to reach 68 TWh in 2050, which accounts for 9% of the total aviation energy demand during the same year. Two pathways are available for decarbonizing this subsector: producing sustainable aviation fuels such as biokerosene or synthetic fuels or introducing hydrogen aircraft powered by fuel cells (Wang et al. 2021). However, the technology readiness level (TRL) for such aircraft is in the fifth stage, which is the component validation in the relevant environment according to NASA's TRL scale (Aerospace Technology Institute 2022). Thus, it is not expected to have any demand for this subsector before 2040.

The forecasted demand is hugely related to the flight traffic and the airplane refueling in each airport. Thus, most of the demand is expected to be concentrated in regions where the big airports of Europe are, such as Heathrow Airport in London, Frankfurt Airport in Germany, and Charles de Gaulle Airport in France. The demand distribution per region is illustrated in Figure 4.11. The region with the most considerable demand is south of the United Kingdom, where seven large airports are located, with a 7 TWh demand. This is followed by the central region of France, where Paris, the capital, is located, along with two of the largest airports in France. The hydrogen demand in this region is expected to reach a value of 4.4 TWh. In

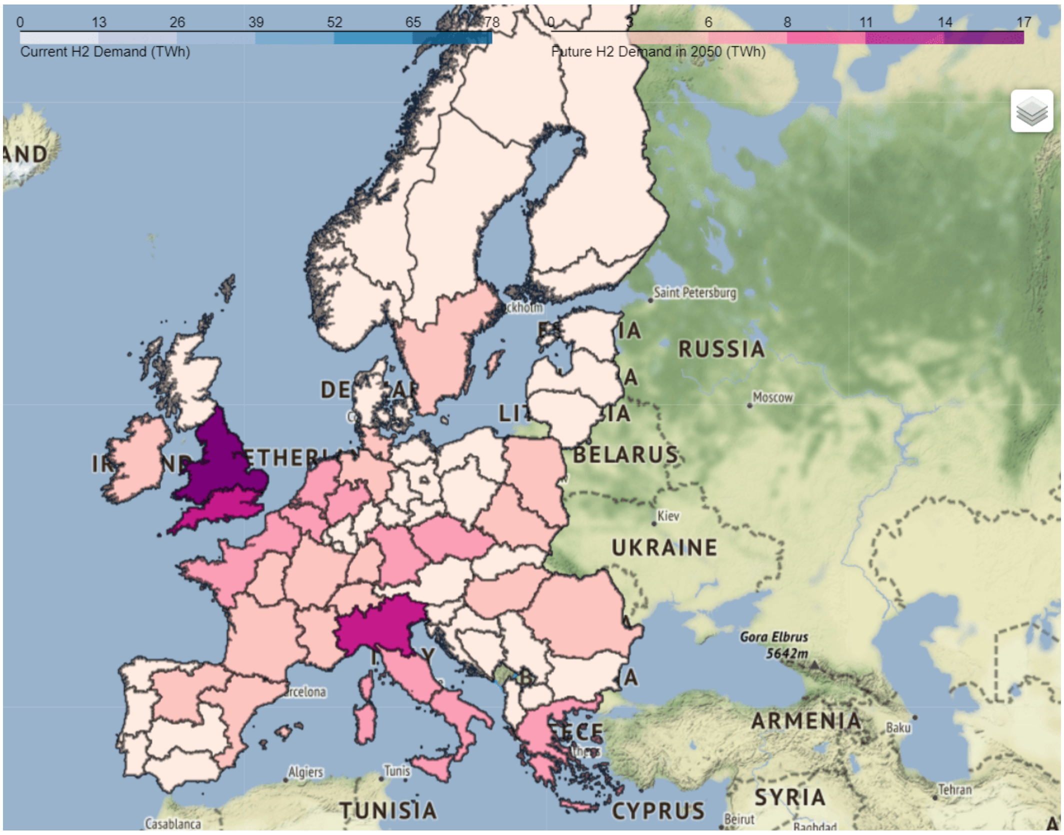

Figure 4.10 The disaggregated European hydrogen demand per region for road transport in 2050 for a medium scenario

Germany, the hydrogen demand for aviation is concentrated in the federal states of Bavaria and Hesse, with an average demand of 2.4 TWh for each state. The hydrogen demand values for aviation for all regions can be found in the appendix A.6.

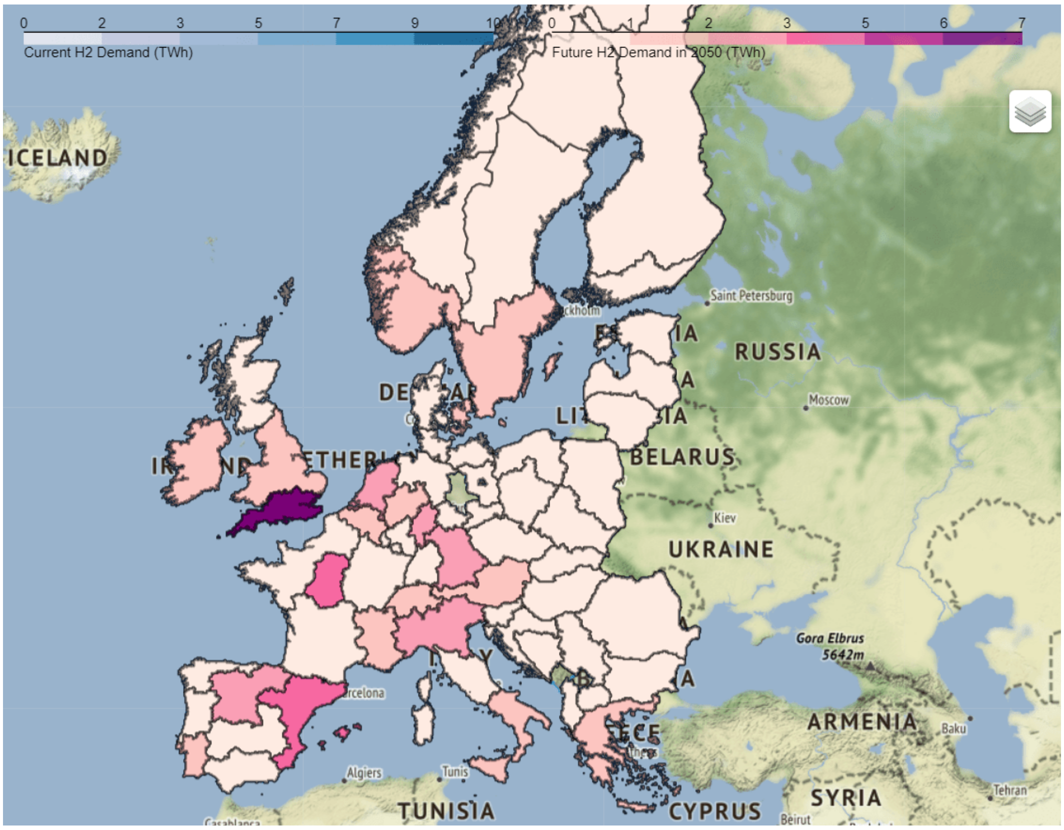

Figure 4.11 The disaggregated European hydrogen demand per region for aviation in 2050

Chapter 5

Discussion

In this thesis, methodologies are developed to disaggregate the future hydrogen demand in Europe for the industrial and transport sector. A regionalization tool is developed to visualize the results of these methodologies, and the tool's output is presented in Chapter 4.

In this chapter, the forecasted disaggregated hydrogen demand is compared with the renewable energy potential for each region in Section 5.1. Section 5.2 presents an analysis of the future hydrogen market, while Section 5.3 discusses the limitations facing hydrogen applications. Lastly, Section 5.4 reflects on the applied methodologies and the regionalization tool.

5.1 Renewable Energy Potential in Europe

The calculated hydrogen demand potentials give a glimpse into the possible spatial disaggregation of future hydrogen demand and the effect of each sector on this distribution. This hydrogen demand must be produced from carbon-free sources such as the blue or green paths in order to reduce GHG emissions and achieve the climate goals set in the Paris agreement in 2015. Refer to Section 2.2 for more information about the different hydrogen production pathways. Blue hydrogen, produced from fossil fuels with a CCS unit installed to capture CO_2 emissions, is considered a transition solution by some until the cost of hydrogen production from renewables decreases (IRENA 2019) (van Renssen 2020a). It can support achieving climate goals at a reasonable cost while meeting the rising hydrogen demand until global and regional markets for hydrogen are developed. This thinking is heavily criticized by others, however, who say that this might lead to lock-in effects hindering complete decarbonization (Energy Monitor 2021).

Producing hydrogen through electrolysis, which converts water into hydrogen and oxygen using electricity and an electrolyzer, is expected to play a significant role in decarbonizing several sectors and achieving the EU goal to become GHG-neutral by 2050 (European Commission 2019). However, electrolysis is only an appealing option for regions with renewable energy potentials. To become cost-competitive with natural gas using CCS, depending on the local gas prices, electricity prices need to reach a value of 10-40 USD/MWh and full load hours of 3,000–6,000 (IEA

2019). Full load hours are the average annual production of a technology divided by its rated power (Morthorst and Kitzing 2016). To produce today's hydrogen demand via electrolysis, which accounts for 70 Mt_{H2}, 3600 TWh of electricity is required. This massive amount of electricity accounts for more than double the total electricity generated from renewables in Europe, which reached 1535.3 TWh in 2021 (IEA 2021a).

On-site green hydrogen production reduces hydrogen costs as transmission costs decrease drastically. However, the price of the renewable electricity used to run the electrolyzer unit is the most significant single cost factor for the on-site production of green hydrogen (IRENA 2020). To achieve competitiveness, this presents an opportunity to produce hydrogen in regions of the world with the best renewable energy potentials.

A geographical analysis is performed to compare the distribution of the forecasted hydrogen demand, the tool's output, with the potential renewable energy in Europe. Figure 5.1 illustrates the expected disaggregated hydrogen demand for the industrial and transport sectors. The highest future potential demands in the industrial and transport sectors are located in the northern part of Europe, such as the central and southern parts of the United Kingdom, The Netherlands, Belgium, and north of France, and the southern part, such as south of Spain, south of France, and Italy. Comparing these regions to the global wind and solar atlases (Figure 5.2) and (Figure 5.3), respectively, electrolyzers operating on electricity produced from onshore and offshore wind turbines could be installed in the north of Europe, where the best wind speeds worldwide are located (DTU Wind Energy and the World Bank Group 2022). In contrast, photovoltaic (PV) technologies could supply electricity to the electrolyzers that could be installed in the south of Europe, where the largest potential for solar energy in Europe is located, to meet the hydrogen demand in the region. Spain, south of France, Italy, and Greece are the best geographical locations to produce electricity from Solar PV in Europe (The World Bank and the International Finance Corporation 2022).

5.2 Future Hydrogen Market

By 2030, studies expect that the industrial, transport, energy, and building sectors will all see a moderate, steady increase in hydrogen demand thanks to various specialized applications such as DRI in steel plants, FCEV in road transport (PwC 2021). Therefore, countries such as Germany and Belgium with low domestic hydrogen supply potential or lacking the necessary conditions to generate enough renewable energy to meet their expected demand will need to import hydrogen to meet their needs (Wang et al. 2021). This clarifies the need to develop a hydrogen market in the future. These regional hydrogen supply and demand variations will widen as the market matures.

There will be strong public opposition to expanding domestic renewable energy sources in Europe to their maximum potential (Haggett 2010). This may be yet another justification for importing green hydrogen from less populated regions near the borders of Europe. However, future large-scale imports are uncertain due to

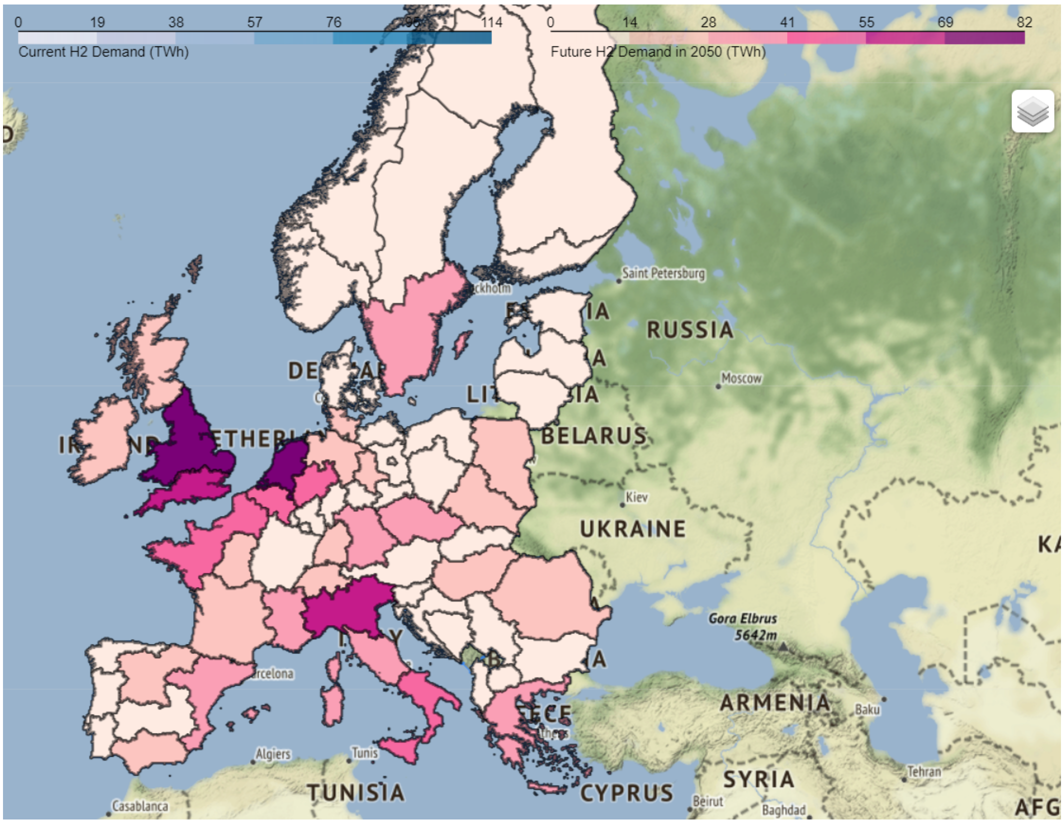

Figure 5.1 The disaggregated European hydrogen demand per region for the industrial and transport sectors in 2050

the reliance on exporting countries, which is usually associated with political and economic risks, and transportation costs. In order to strike a balance between the expansion of renewable energy capacities and dependent on imports with associated costs, a supranational policy must be set in Europe.

In some regions of the Middle East, Africa, Russia, China, the US, and Australia, the cost of producing green hydrogen will be between 1.03 and 1.55 USD/kg by 2050. Production costs will be around 2.06 USD/kg over the same period in areas with limited renewable resources, such as much of Europe, Japan, or Korea, making these markets candidates as importers of green hydrogen (PwC 2021).

Most current industrial facilities are strategically located near ports and industrial hubs, as demonstrated in Chapter 4, making importing feedstock and energy carriers easier. Global hubs for hydrogen export and import will emerge, similar to today's oil and gas hubs, but with new players in the renewable energy-rich regions (Wang et al. 2021).

5.3 Limitations of Hydrogen Use

The production path with the lowest CO_2 emissions is green hydrogen. The regions with scarce water resources, such as Australia, also have the highest po-

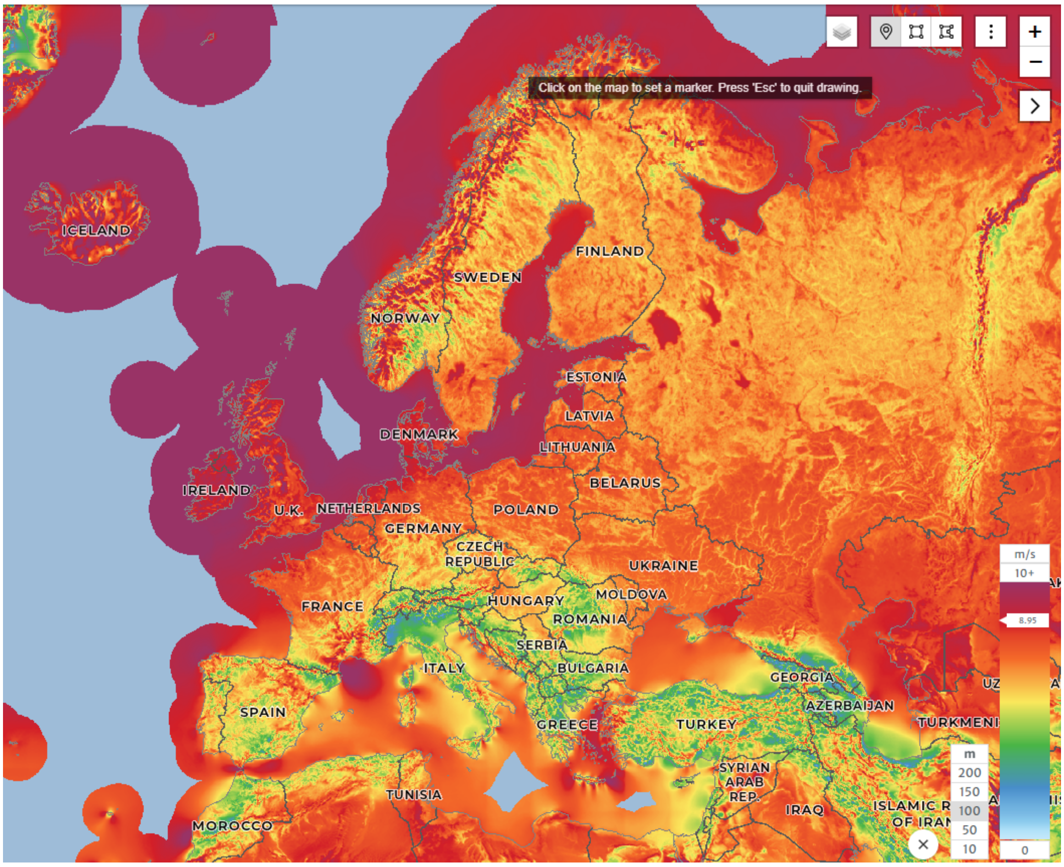

Figure 5.2 Wind speeds across Europe (DTU Wind Energy and the World Bank Group 2022)

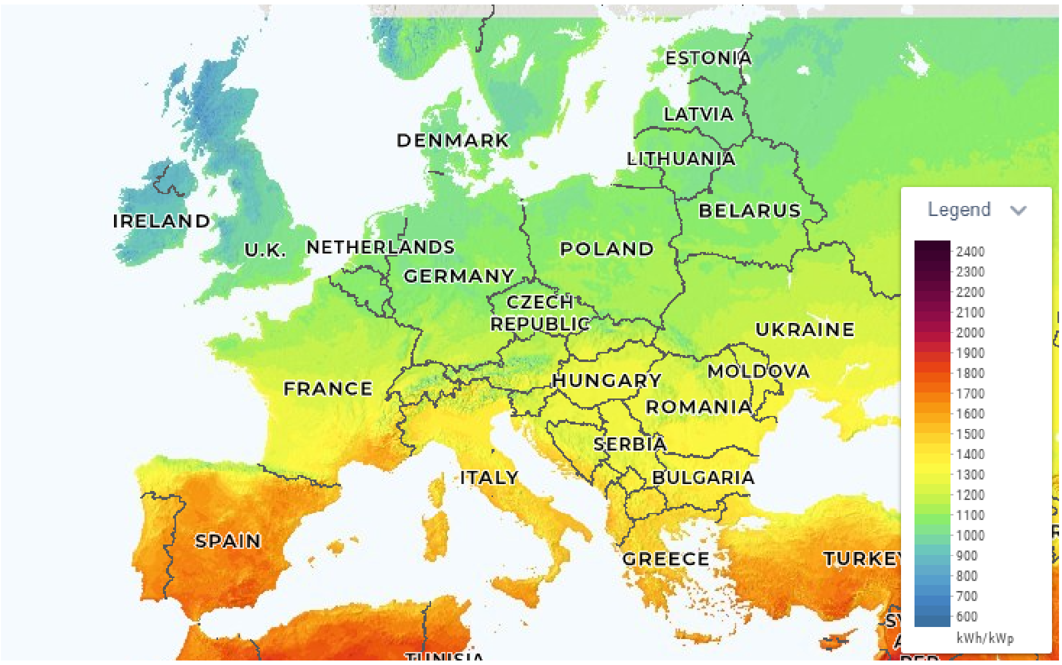

Figure 5.3 Potential of solar energy across Europe (The World Bank and the International Finance Corporation 2022)

tential for renewable energy sources and are expected to become export countries in the future market (Ejaz Qureshi, Hanjra, and Ward 2013). Energy demand increases if seawater desalination is needed or electrolyzers that can split seawater are installed. The benefits and drawbacks of using hydrogen in the industrial and transport sectors are discussed in the following sections.

5.3.1 Industrial Sector

To the best of our knowledge, hydrogen is needed in the industrial sector because some processes cannot be decarbonized in any other way. The expansion of the hydrogen infrastructure is being driven by large consumers in the steel industry and ammonia production sites. Moreover, investment decisions determine the road for the future in the industrial sector, as high investments spanning several decades are deterrents to using hydrogen. They could prevent the transition to a hydrogen economy and the achievement of GHG emission targets (Agora Energiewende und Wuppertal Institut 2019).

5.3.2 Transport Sector

By 2050, it is anticipated that 40% to 100% of German road travel will be electrified (Ruhnau et al. 2019). The scenarios reviewed in the Ruhnau literature do not favor either directly or indirectly electrifying road transportation. The indirect electrification in the transport sector by using hydrogen has several benefits. First of all, the fuel cell is regarded as being highly developed and versatile. Additionally, the operating range of FCEV is larger, and the refueling time is shorter than with a battery electric vehicle (BEV). Even though fuel-cell electric vehicles (FCEVs) compete directly with BEVs, they are currently more expensive, less efficient, and have even worse refueling infrastructure. However, the costs of hydrogen and fuel-cell electric vehicles are anticipated to drop significantly (European Commission 2018). The larger operating range and the shorter refueling time currently make FCEV more suitable for heavy-duty applications such as buses and trucks.

5.4 Regionalization Tool and Methodology Limitations

The lack of data that would be useful for the regionalization of hydrogen demand was one of the challenges faced during the tool development. Site-specific information that can be used to deduce the activity or operation is usually protected, especially for the industrial sector. For example, ammonia is an intermediate product in the fertilizer production process. As a result, not all plants provide individual ammonia production volume statements. Therefore, not all sites might have been covered in the database. Compared to ammonia, the availability of data for steel production is significantly better as many sources are available such as (European Steel Association 2021), (Global Energy Monitor 2022), and (World Steel Association 2021). Thus, a cross-check of the data for this subsector was possible to ensure the quality of the developed database. For refineries, only one open-access database was found (Concawe 2021); thus, no data validation could be performed. However, the data availability for refineries was better than for the ammonia plants. The list of industrial sites will undoubtedly need to be updated and expanded for future research.

In order to regionalize a potential future hydrogen demand in the industrial sector, the methodological approach presented in this thesis used statistical values on actual plant production and a specific hydrogen process value. There is no agreed-upon definition of precise specific values of hydrogen requirement for a production process. (Welder, Ryberg, et al. 2018) provide the specific values used in this thesis which are summarized in Table 4.2. The validity of these assumptions would be improved by comparison with other works.

The lack of data was also a challenge that existed when developing a methodology for the transport sector. This leads to the use of the disaggregated number of registered vehicles per LAUs (Eurostat 2021a), which limits the application of the methodology only to Europe or any other regions with data reported and disaggregated for each level of the national administrative subdivisions similar to NUTS regions (Eurostat 2021b). Moreover, the vehicle yearly traveled distance is not recorded for some countries. Where that is the case, it is assumed that it is equal to the traveled distance of a vehicle in a country with both population and area similar to its own. Finally, the hydrogen consumption for each type of vehicle was calculated based on the current average values in the market. Thus, updating these values is considered a crucial step in the future.

Chapter 6

Conclusion

The distribution of the estimated hydrogen demand potentials in Europe for the industrial and transport sectors is presented in this thesis. For this purpose, a regionalization tool called RegTool is developed to visualize the disaggregation of the expected future hydrogen demand per region. For the industrial sector, process-specific values and production site data are used to calculate the hydrogen demand for the industrial facilities. The industrial facilities included in the tool's database are steel plants, ammonia production sites, and refineries. The literature review within this thesis's scope demonstrates that hydrogen-based alternatives in the industry are anticipated to become available in the next decade. This includes substituting grey hydrogen produced through steam methane reforming (SMR) from natural gas used as a feedstock in specific industrial processes with fossil-free hydrogen. The cost of producing green hydrogen has been the most significant barrier to developing ways to supply energy demand without GHG emissions thus far. For the transport sector, road transport and aviation are covered in this thesis and the resulting regionalization tool. Hydrogen consumption and the annual traveled distance per vehicle are used in calculating the hydrogen demand in road transport.

The assumption that the industrial and transport sectors will be crucial pillars in establishing a hydrogen economy motivated this thesis to investigate the expected distribution of future hydrogen demand across Europe. The results of the regionalization tool highlight the extent to which the decarbonization of these sectors is a challenge for Europe. Developing a hydrogen market is vital as the demand is already observable and expected to increase. This thesis includes in total 246 industrial facilities across Europe. Based on the process-specific methodology applied in this thesis and the production values of 2020, these industrial facilities have a total estimated potential hydrogen demand of 634.5 TWh/year. This would entail completely switching to green hydrogen and using hydrogen-based alternatives in all plants included in this thesis. A market penetration scenario is chosen in this thesis to investigate the diffusion of FCEV in the market for road transport. The investigated scenario assumes that 50% of passenger vehicles, 50% of trucks, and 60% of buses in the European market will be powered by hydrogen in 2050 hence rendering a total demand for road transport in Europe of 1033 TWh/year while the hydrogen demand in all of Europe's airports is expected to reach 639 TWh/year in 2050.

A key takeaway from the massive total potential hydrogen demand for the industrial and transport sectors is that a significant amount of renewable electricity will be required to produce this demand through the green pathway. Producing the resulting expected future hydrogen demand of the regionalization tool for these two sectors, which has a total expected value of 2306.5 TWh in 2050, would require almost a total of 3600 TWh of electricity if it was to be supplied via electrolysis (IEA 2019), which is two times larger than the total electricity generated, from renewable sources in Europe in 2021. Thus for hydrogen to play a role in the European energy transition, establishing a hydrogen market, importing green hydrogen from countries with higher renewable energy potential and less-populated regions, and setting more investments in expanding renewables capacities are required in the following decades.

The disaggregated hydrogen demand is concentrated in Europe in highly populated regions or regions with either renewable energy potentials or near ports, making producing green hydrogen or importing it from other countries easier. However, hydrogen's potential contribution to the energy system is still unclear. Thus, more decisions will need to be taken, and significant investments must be initiated in the coming years to meet the goals of the Paris Agreement.

Chapter 7

Outlook

The results of a research work usually raise more questions than they answer and open more opportunities for improvements. Indeed, this also applies to the current work done within the scope of this thesis. Thus, several suggestions that might help answer those questions are proposed in the following.

An add-on for the work done in the course of this thesis is the development of a database for the industrial facilities in Europe and one for the number of registered vehicles per region. However, this reveals the challenges faced while gathering this data. With more time and resources, these databases could be improved by obtaining more accurate and detailed information on plants and processes by directly contacting the facilities' management or collaborating with other research groups. Such a strategy would enable the regionalization tool to be more accurate and become more comprehensive. The tool could be enhanced for the industrial sector by regularly updating and adding more production sites for ammonia, steel, and refineries that will start operating in the future. Moreover, the tool could be further expanded to include more energy-intensive industries with future potential hydrogen demand, such as cement, and glass plants which are not considered in the tool due to their current low TRL (Neuwirth et al. 2022). Finally, there is no agreed-upon definition of precise specific values of hydrogen requirement for a production process. The specific values used in this thesis which are summarized in Table 4.2 would be improved by comparing them with other works. For the transport sector, the hydrogen consumption for each type of vehicle was calculated based on the current average values in the market. Thus, updating these values is considered a crucial step in the future. Furthermore, the tool could be expanded to include rail and maritime transport. More sectors, such as buildings, should be included in the tool in order to cover all expected future hydrogen demand for all applications.

Future growth opportunities in electrolysis and fuel cells will lead to the need to install more wind, solar, and other renewable energy capacities to supply this rising hydrogen demand. However, future developments in the hydrogen market are highly dynamic and thus uncertain. The results of the tool are partially based on these forecasts, which would influence its output. Moreover, current investment decisions will determine the road for the future, as high investments spanning several decades are deterrents to using hydrogen. They could prevent the transition to a hydrogen economy and the achievement of GHG emission targets.

Appendix A

Appendix

A.1 Appendix: The disaggregated hydrogen demand values per region for steel plants

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
AT	8.238	2050	Industrial Sector	Steel
BA	0.9676	2050	Industrial Sector	Steel
BE	8.1208	2050	Industrial Sector	Steel
BG	0.5926	2050	Industrial Sector	Steel
CH	1.6128	2050	Industrial Sector	Steel
CZ	5.2503	2050	Industrial Sector	Steel
DE_BAY	1.0024	2050	Industrial Sector	Steel
DE_BRA	4.4172	2050	Industrial Sector	Steel
DE_BW	2.1237	2050	Industrial Sector	Steel
DE_HE	0.3398	2050	Industrial Sector	Steel
DE_HH	0.9344	2050	Industrial Sector	Steel
DE_NDSB	9.9579	2050	Industrial Sector	Steel
DE_NRW	16.5307	2050	Industrial Sector	Steel
DE_SAAR	5.0968	2050	Industrial Sector	Steel
DE_SAX	0.9259	2050	Industrial Sector	Steel
DE_TH	0.9344	2050	Industrial Sector	Steel
EL	1.125	2050	Industrial Sector	Steel
ES_Central	0.9509	2050	Industrial Sector	Steel
ES_East	2.1213	2050	Industrial Sector	Steel
ES_North	3.5039	2050	Industrial Sector	Steel
ES_Northwest	5.0123	2050	Industrial Sector	Steel
ES_South	1.8287	2050	Industrial Sector	Steel
FI_North	3.9112	2050	Industrial Sector	Steel
FI_South	0.8853	2050	Industrial Sector	Steel
FR_Central	1.8129	2050	Industrial Sector	Steel
FR_East	0.8742	2050	Industrial Sector	Steel
FR_North	7.6367	2050	Industrial Sector	Steel
FR_Southeast	4.7853	2050	Industrial Sector	Steel

Table A.1 continued from previous page

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
FR_Southwest	1.1043	2050	Industrial Sector	Steel
HR	0.1411	2050	Industrial Sector	Steel
HU	2.0989	2050	Industrial Sector	Steel
IT_Central	1.1804	2050	Industrial Sector	Steel
IT_North	16.3425	2050	Industrial Sector	Steel
IT_South	10.2792	2050	Industrial Sector	Steel
LU	2.4041	2050	Industrial Sector	Steel
NL	7.7051	2050	Industrial Sector	Steel
NO_North	0.4994	2050	Industrial Sector	Steel
PL_East	0.7167	2050	Industrial Sector	Steel
PL_South	7.8273	2050	Industrial Sector	Steel
PT_North	0.7079	2050	Industrial Sector	Steel
PT_South	1.2978	2050	Industrial Sector	Steel
RO	3.7997	2050	Industrial Sector	Steel
RS	1.9345	2050	Industrial Sector	Steel
SE_Central	1.7438	2050	Industrial Sector	Steel
SE_North	2.0135	2050	Industrial Sector	Steel
SE_South	1.5644	2050	Industrial Sector	Steel
SI	0.7555	2050	Industrial Sector	Steel
SK	5.4485	2050	Industrial Sector	Steel
UK_Central	7.9415	2050	Industrial Sector	Steel

A.2 Appendix: The disaggregated hydrogen demand values per region for ammonia production sites

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
AT	5.559	2050	Industrial Sector	Chemical Industry
BE	4.6676	2050	Industrial Sector	Chemical Industry
BG	4.2068	2050	Industrial Sector	Chemical Industry
CZ	4.2068	2050	Industrial Sector	Chemical Industry
DE_BAY	4.9355	2050	Industrial Sector	Chemical Industry
DE_RP	8.7742	2050	Industrial Sector	Chemical Industry
DE_SAN	12.0695	2050	Industrial Sector	Chemical Industry
DE_SH	8.0129	2050	Industrial Sector	Chemical Industry
EE	2.1034	2050	Industrial Sector	Chemical Industry
ES_Central	2.0133	2050	Industrial Sector	Chemical Industry
ES_South	4.0265	2050	Industrial Sector	Chemical Industry
FR_North	9.8559	2050	Industrial Sector	Chemical Industry
IT_North	6.0097	2050	Industrial Sector	Chemical Industry
LT	9.5154	2050	Industrial Sector	Chemical Industry
NL	19.0307	2050	Industrial Sector	Chemical Industry
NO_South	5.0081	2050	Industrial Sector	Chemical Industry
UK_Central	3.0049	2050	Industrial Sector	Chemical Industry

A.3 Appendix: The disaggregated hydrogen demand values per region for refineries

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
AL	1.5563	2050	Industrial Sector	Refineries
AT	10.0641	2050	Industrial Sector	Refineries
BA	1.5563	2050	Industrial Sector	Refineries
BE	34.7575	2050	Industrial Sector	Refineries
BG	6.0177	2050	Industrial Sector	Refineries
CH	3.5276	2050	Industrial Sector	Refineries
CZ	9.1304	2050	Industrial Sector	Refineries
DE_BAY	21.2696	2050	Industrial Sector	Refineries
DE_BRA	11.4129	2050	Industrial Sector	Refineries
DE_BW	16.0818	2050	Industrial Sector	Refineries
DE_HH	7.989	2050	Industrial Sector	Refineries
DE_NDSB	5.084	2050	Industrial Sector	Refineries
DE_NRW	29.9849	2050	Industrial Sector	Refineries
DE_SAN	11.8279	2050	Industrial Sector	Refineries
DE_SH	5.4989	2050	Industrial Sector	Refineries
DK_East	5.4989	2050	Industrial Sector	Refineries
DK_West	3.5276	2050	Industrial Sector	Refineries
EL	25.5234	2050	Industrial Sector	Refineries
ES_Central	7.7815	2050	Industrial Sector	Refineries
ES_East	27.4947	2050	Industrial Sector	Refineries
ES_North	11.4129	2050	Industrial Sector	Refineries
ES_Northwest	6.2252	2050	Industrial Sector	Refineries
ES_South	22.3071	2050	Industrial Sector	Refineries
FI_South	10.6866	2050	Industrial Sector	Refineries
FR_North	36.4175	2050	Industrial Sector	Refineries
FR_Southeast	23.4484	2050	Industrial Sector	Refineries
HR	4.6689	2050	Industrial Sector	Refineries
HU	8.6116	2050	Industrial Sector	Refineries
IE_NIR	3.7351	2050	Industrial Sector	Refineries
IT_Central	24.486	2050	Industrial Sector	Refineries
IT_North	20.0245	2050	Industrial Sector	Refineries
IT_South	43.9916	2050	Industrial Sector	Refineries
LT	9.8566	2050	Industrial Sector	Refineries
NL	63.8086	2050	Industrial Sector	Refineries
NO_South	10.5829	2050	Industrial Sector	Refineries
PL_East	19.402	2050	Industrial Sector	Refineries
PL_North	10.8941	2050	Industrial Sector	Refineries
PL_South	0.6225	2050	Industrial Sector	Refineries
PT_South	11.7242	2050	Industrial Sector	Refineries
RO	12.8654	2050	Industrial Sector	Refineries
SE_South	22.8258	2050	Industrial Sector	Refineries
SK	6.0177	2050	Industrial Sector	Refineries

Table A.3 continued from previous page

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
UK_Central	39.5302	2050	Industrial Sector	Refineries
UK_North	7.7815	2050	Industrial Sector	Refineries
UK_South	13.488	2050	Industrial Sector	Refineries

A.4 Appendix: The disaggregated hydrogen demand values per region for the industrial sector

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
AL	1.6737	2050	Industrial Sector	Total
AT	22.1225	2050	Industrial Sector	Total
BA	2.5295	2050	Industrial Sector	Total
BE	47.9303	2050	Industrial Sector	Total
BG	10.033	2050	Industrial Sector	Total
CH	5.22	2050	Industrial Sector	Total
CZ	17.4997	2050	Industrial Sector	Total
DE_BAY	27.3232	2050	Industrial Sector	Total
DE_BRA	16.1802	2050	Industrial Sector	Total
DE_BW	19.1726	2050	Industrial Sector	Total
DE_HE	0.3005	2050	Industrial Sector	Total
DE_HH	9.4178	2050	Industrial Sector	Total
DE_NDSB	14.2742	2050	Industrial Sector	Total
DE_NRW	46.8657	2050	Industrial Sector	Total
DE_RP	6.3351	2050	Industrial Sector	Total
DE_SAAR	4.5077	2050	Industrial Sector	Total
DE_SAN	21.4342	2050	Industrial Sector	Total
DE_SAX	0.8189	2050	Industrial Sector	Total
DE_SH	11.6991	2050	Industrial Sector	Total
DE_TH	0.8264	2050	Industrial Sector	Total
DK_East	5.9136	2050	Industrial Sector	Total
DK_West	3.7936	2050	Industrial Sector	Total
EE	1.5187	2050	Industrial Sector	Total
EL	28.4427	2050	Industrial Sector	Total
ES_Central	10.6629	2050	Industrial Sector	Total
ES_East	31.4442	2050	Industrial Sector	Total
ES_North	15.3724	2050	Industrial Sector	Total
ES_Northwest	11.1276	2050	Industrial Sector	Total
ES_South	28.5135	2050	Industrial Sector	Total
FI_North	3.4592	2050	Industrial Sector	Total
FI_South	12.2754	2050	Industrial Sector	Total
FR_Central	1.6033	2050	Industrial Sector	Total
FR_East	0.7732	2050	Industrial Sector	Total
FR_North	53.0337	2050	Industrial Sector	Total
FR_Southeast	29.4486	2050	Industrial Sector	Total
FR_Southwest	0.9767	2050	Industrial Sector	Total
HR	5.1458	2050	Industrial Sector	Total
HU	11.1171	2050	Industrial Sector	Total
IE_NIR	4.0168	2050	Industrial Sector	Total
IT_Central	27.3761	2050	Industrial Sector	Total
IT_North	40.3273	2050	Industrial Sector	Total
IT_South	56.3997	2050	Industrial Sector	Total

Table A.4 continued from previous page

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
LT	17.47	2050	Industrial Sector	Total
LU	2.1262	2050	Industrial Sector	Total
NL	89.1747	2050	Industrial Sector	Total
NO_North	0.4417	2050	Industrial Sector	Total
NO_South	14.9967	2050	Industrial Sector	Total
PL_East	21.4988	2050	Industrial Sector	Total
PL_North	11.7156	2050	Industrial Sector	Total
PL_South	7.5922	2050	Industrial Sector	Total
PT_North	0.6261	2050	Industrial Sector	Total
PT_South	13.756	2050	Industrial Sector	Total
RO	17.196	2050	Industrial Sector	Total
RS	1.711	2050	Industrial Sector	Total
SE_Central	1.5423	2050	Industrial Sector	Total
SE_North	1.7808	2050	Industrial Sector	Total
SE_South	25.9306	2050	Industrial Sector	Total
SI	0.6681	2050	Industrial Sector	Total
SK	11.2902	2050	Industrial Sector	Total
UK_Central	51.7041	2050	Industrial Sector	Total
UK_North	8.3683	2050	Industrial Sector	Total
UK_South	14.505	2050	Industrial Sector	Total

A.5 Appendix: The disaggregated hydrogen demand values per region for road transport

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
AL	0.5678	2050	Transport Sector	Road Transport Total
AT	5.9034	2050	Transport Sector	Road Transport Total
BA	0.9904	2050	Transport Sector	Road Transport Total
BE	6.1054	2050	Transport Sector	Road Transport Total
BG	1.36	2050	Transport Sector	Road Transport Total
CH	3.8126	2050	Transport Sector	Road Transport Total
CZ	6.7293	2050	Transport Sector	Road Transport Total
DE_BAY	6.8391	2050	Transport Sector	Road Transport Total
DE_BER	0.0129	2050	Transport Sector	Road Transport Total
DE_BRA	1.2701	2050	Transport Sector	Road Transport Total
DE_BW	5.1404	2050	Transport Sector	Road Transport Total
DE_HE	2.7143	2050	Transport Sector	Road Transport Total
DE_HH	0.5833	2050	Transport Sector	Road Transport Total
DE_MV	0.724	2050	Transport Sector	Road Transport Total
DE_NDSB	3.6696	2050	Transport Sector	Road Transport Total
DE_NRW	5.6551	2050	Transport Sector	Road Transport Total
DE_RP	2.0478	2050	Transport Sector	Road Transport Total
DE_SAAR	0.4359	2050	Transport Sector	Road Transport Total
DE_SAN	1.4011	2050	Transport Sector	Road Transport Total
DE_SAX	2.3883	2050	Transport Sector	Road Transport Total
DE_SH	3.271	2050	Transport Sector	Road Transport Total
DE_TH	0.8285	2050	Transport Sector	Road Transport Total
DK_East	1.4589	2050	Transport Sector	Road Transport Total
DK_West	1.7535	2050	Transport Sector	Road Transport Total
EE	0.7073	2050	Transport Sector	Road Transport Total
EL	6.3543	2050	Transport Sector	Road Transport Total
ES_Central	1.1586	2050	Transport Sector	Road Transport Total
ES_East	4.9755	2050	Transport Sector	Road Transport Total
ES_North	3.8155	2050	Transport Sector	Road Transport Total
ES_Northwest	1.366	2050	Transport Sector	Road Transport Total
ES_South	2.4481	2050	Transport Sector	Road Transport Total
FI_North	1.9114	2050	Transport Sector	Road Transport Total
FI_South	1.6589	2050	Transport Sector	Road Transport Total
FR_Central	4.0176	2050	Transport Sector	Road Transport Total
FR_East	3.1878	2050	Transport Sector	Road Transport Total
FR_North	6.7003	2050	Transport Sector	Road Transport Total
FR_Southeast	4.1899	2050	Transport Sector	Road Transport Total
FR_Southwest	5.1885	2050	Transport Sector	Road Transport Total
HR	1.0979	2050	Transport Sector	Road Transport Total
HU	3.0559	2050	Transport Sector	Road Transport Total
IE_NIR	4.0264	2050	Transport Sector	Road Transport Total
IT_Central	6.425	2050	Transport Sector	Road Transport Total

Table A.5 continued from previous page

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
IT_North	11.1769	2050	Transport Sector	Road Transport Total
IT_South	7.2036	2050	Transport Sector	Road Transport Total
LT	1.4604	2050	Transport Sector	Road Transport Total
LU	0.5741	2050	Transport Sector	Road Transport Total
LV	0.989	2050	Transport Sector	Road Transport Total
MK	0.5011	2050	Transport Sector	Road Transport Total
NL	8.1517	2050	Transport Sector	Road Transport Total
NO_Central	1.3235	2050	Transport Sector	Road Transport Total
NO_North	0.4117	2050	Transport Sector	Road Transport Total
NO_South	0.7925	2050	Transport Sector	Road Transport Total
PL_East	3.9322	2050	Transport Sector	Road Transport Total
PL_North	1.8827	2050	Transport Sector	Road Transport Total
PL_South	4.4844	2050	Transport Sector	Road Transport Total
PL_West	2.7175	2050	Transport Sector	Road Transport Total
PT_North	1.2891	2050	Transport Sector	Road Transport Total
PT_South	0.9142	2050	Transport Sector	Road Transport Total
RO	4.6876	2050	Transport Sector	Road Transport Total
RS	1.4667	2050	Transport Sector	Road Transport Total
SE_Central	0.9661	2050	Transport Sector	Road Transport Total
SE_North	0.1648	2050	Transport Sector	Road Transport Total
SE_South	4.51	2050	Transport Sector	Road Transport Total
SI	1.434	2050	Transport Sector	Road Transport Total
SK	2.0353	2050	Transport Sector	Road Transport Total
UK_Central	16.6749	2050	Transport Sector	Road Transport Total
UK_North	2.6604	2050	Transport Sector	Road Transport Total
UK_South	12.0696	2050	Transport Sector	Road Transport Total

A.6 Appendix: The disaggregated hydrogen demand values per region for aviation

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
AL	0.1237	2050	Transport Sector	Air Transport
AT	1.6599	2050	Transport Sector	Air Transport
BA	0.0402	2050	Transport Sector	Air Transport
BE	1.6472	2050	Transport Sector	Air Transport
BG	0.34	2050	Transport Sector	Air Transport
CH	2.265	2050	Transport Sector	Air Transport
CZ	0.7309	2050	Transport Sector	Air Transport
DE_BAY	2.4801	2050	Transport Sector	Air Transport
DE_BRA	1.0834	2050	Transport Sector	Air Transport
DE_BW	0.5684	2050	Transport Sector	Air Transport
DE_HE	2.383	2050	Transport Sector	Air Transport
DE_HH	0.8511	2050	Transport Sector	Air Transport
DE_MV	0.0054	2050	Transport Sector	Air Transport
DE_NDSB	0.3417	2050	Transport Sector	Air Transport
DE_NRW	1.7195	2050	Transport Sector	Air Transport
DE_RP	0.048	2050	Transport Sector	Air Transport
DE_SAAR	0.0193	2050	Transport Sector	Air Transport
DE_SAX	0.1375	2050	Transport Sector	Air Transport
DE_SH	0.0079	2050	Transport Sector	Air Transport
DE_TH	0.0052	2050	Transport Sector	Air Transport
DK_East	1.5716	2050	Transport Sector	Air Transport
DK_West	0.1864	2050	Transport Sector	Air Transport
EE	0.1534	2050	Transport Sector	Air Transport
EL	1.8282	2050	Transport Sector	Air Transport
ES_Central	0.0014	2050	Transport Sector	Air Transport
ES_East	3.8912	2050	Transport Sector	Air Transport
ES_North	2.7386	2050	Transport Sector	Air Transport
ES_Northwest	0.1452	2050	Transport Sector	Air Transport
ES_South	0.978	2050	Transport Sector	Air Transport
FI_North	0.138	2050	Transport Sector	Air Transport
FI_South	1.1207	2050	Transport Sector	Air Transport
FR_Central	4.3816	2050	Transport Sector	Air Transport
FR_East	0.079	2050	Transport Sector	Air Transport
FR_North	0.5155	2050	Transport Sector	Air Transport
FR_Southeast	1.7206	2050	Transport Sector	Air Transport
FR_Southwest	0.9876	2050	Transport Sector	Air Transport
HR	0.3531	2050	Transport Sector	Air Transport
HU	0.4711	2050	Transport Sector	Air Transport
IE_NIR	1.4552	2050	Transport Sector	Air Transport
IT_Central	0.9464	2050	Transport Sector	Air Transport
IT_North	3.3121	2050	Transport Sector	Air Transport
IT_South	1.3034	2050	Transport Sector	Air Transport

Table A.6 continued from previous page

Region	Value (TWh)	Year	Demand Sector	Demand Subsector
LT	0.1698	2050	Transport Sector	Air Transport
LU	0.1777	2050	Transport Sector	Air Transport
LV	0.354	2050	Transport Sector	Air Transport
MK	0.0401	2050	Transport Sector	Air Transport
NL	2.8911	2050	Transport Sector	Air Transport
NO_Central	0.296	2050	Transport Sector	Air Transport
NO_North	0.3598	2050	Transport Sector	Air Transport
NO_South	2.1045	2050	Transport Sector	Air Transport
PL_East	0.8721	2050	Transport Sector	Air Transport
PL_North	0.1158	2050	Transport Sector	Air Transport
PL_South	0.2105	2050	Transport Sector	Air Transport
PL_West	0.0828	2050	Transport Sector	Air Transport
PT_North	0.446	2050	Transport Sector	Air Transport
PT_South	1.8986	2050	Transport Sector	Air Transport
RO	0.8876	2050	Transport Sector	Air Transport
RS	0.3491	2050	Transport Sector	Air Transport
SE_Central	0.1237	2050	Transport Sector	Air Transport
SE_North	0.0971	2050	Transport Sector	Air Transport
SE_South	2.0712	2050	Transport Sector	Air Transport
SI	0.105	2050	Transport Sector	Air Transport
SK	0.0325	2050	Transport Sector	Air Transport
UK_Central	1.6188	2050	Transport Sector	Air Transport
UK_North	0.996	2050	Transport Sector	Air Transport
UK_South	6.9651	2050	Transport Sector	Air Transport

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