

LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT  
School of Energy Systems  
Department of Environmental Technology  
Sustainability Science and Solutions  
Master's thesis 2023

Vikram Singh Chauhan

Environmental Sustainability Assessment of Green Hydrogen in Transport Sector

Examiner: Ville Uusitalo  
Associate professor, D.Sc. (Tech.)  
Lauri Leppäkoski  
Junior Researcher, M.Sc.

## ABSTRACT

LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT  
School of Energy Systems  
Department of Environmental Technology  
Sustainability Science and Solutions  
Master's thesis 2023

Vikram Singh Chauhan

Environmental Sustainability Assessment of Green Hydrogen in Transport Sector

Master's Thesis

2023

69 pages, 36 figures

Examiners: Associate professor Ville Uusitalo  
Junior researcher Lauri Leppäkoski

This study investigates the fundamental factors that contribute to high levels of air pollution in a variety of urban regions, as well as the viability of various fuels for transportation and the hydrogen energy system's potential role in addressing these issues. The majority of vehicle fleets used for transportation across the world run on fuels that are derived from fossil resources. The development of economic activity has resulted in a rise in the provision of transportation services, which has led to an increase in both the consumption of fuel and the emissions of greenhouse gases (GHG), most notably uncontrolled emissions of carbon dioxide. The use of hydrogen as a fuel for automobiles would improve the reliability of the energy supply while simultaneously reducing emissions of greenhouse gases. For the European Union's (EU's) road transportation sector, an analysis of the practicability of a hydrogen energy system, encompassing the system's resources, production methods, storage, fuel transit, dispensing, and consumption, has been carried out.

## ACKNOWLEDGEMENTS

First and foremost, I am indebted to my advisors, Professor Ville Uusitalo and junior researcher Lauri Leppäkoski, for their important counsel, constant support, and remarkable patience during my thesis. Their vast knowledge, counsel, and vast experiences have always inspired me in my academic study and daily life. I'd like to sincerely thank them for their patience when I was writing my thesis. Their critiques and ongoing assistance with my thesis opened the way to its completion. This thesis has unquestionably enhanced my understanding of the ongoing research and future potential for Green Hydrogen as a transportation fuel.

In addition, I would like to express my gratitude to LUT University and each individual member of the department. My time spent studying and living in Finland has been absolutely fantastic thanks to their generous assistance and support.

Finally, I would like to use this opportunity to thank my family and all of my close friends. My ability to pursue a master's degree and finish my thesis would not have been feasible if they had not provided me with the amazing support, understanding, and encouragement that they have shown over the last several years.

## TABLE OF CONTENTS

<b>ABSTRACT</b>	<b>2</b>
<b>ACKNOWLEDGEMENTS</b>	<b>1</b>
<b>TABLE OF CONTENTS</b>	<b>4</b>
<b>LIST OF SYMBOLS AND ABBREVIATIONS</b>	<b>5</b>
<b>1. INTRODUCTION</b>	<b>6</b>
1.1 Research Problem	7
1.2 Objective of work	8
1.3 Framework	8
1.4 Research questions	8
<b>2. Overview of Global Transport Sector</b>	<b>10</b>
2.1 Overview of Transport sector in Europe	17
<b>3. Green Hydrogen Production</b>	<b>24</b>
3.1 Green Hydrogen as a future fuel	24
3.2 Hydrogen Production	30
3.2.1 Natural Gas Reforming	31
3.2.2 Gasification	32
3.2.3 Renewable Liquid Reforming	37
3.2.4 Electrolysis	38
3.2.5 Solar Thermochemical Water-Splitting	40
3.2.6 Photoelectrochemical (PEC)	40
<b>4. Carbon Footprint of Hydrogen Production</b>	<b>42</b>
4.1 Carbon Footprint using Steam methane reforming process	42
4.2 Carbon Footprint using Electrolysis of Water	44
4.3 Carbon Footprint using Coal and Lignite Gasification	47
<b>5. Discussion</b>	<b>51</b>
5.1 Why is green hydrogen a better fuel than conventional fossil fuels in transportation	51
5.2 Is it possible to convert the whole transportation sector to hydrogen driven	55
5.3 Predictions on future hydrogen production and transport sector in Europe	57
<b>6. Conclusion</b>	<b>62</b>
<b>7. References</b>	<b>65</b>

## LIST OF SYMBOLS AND ABBREVIATIONS

EU	European Union
GHG	GreenHouse Gases
CO	Carbon Monoxide
HC	Hydrocarbon Monoxide
NO <sub>x</sub>	Nitrogen Oxides
PM	Particulate Matter
CO <sub>2</sub>	Carbon Dioxide
Mtoe	Million Tons of Equivalent
LDV	Light Duty Vehicle
COVID	Coronavirus Disease- 19
PM	Particulate Matter
AVI	Avoid-Shift-Improve approach
GW	Gigawatt
CCUS	Carbon Capture, Utilization and Storage
LHV	Lower Heating Value
TWSC	Thermochemical Water-Splitting Cycles
PEC	Photoelectrochemical
SMR	Steam Methane Reforming
H <sub>2</sub>	Hydrogen
SCF	Standard Cubic Feet
BOP	Balance Of Plant
PEM	Proton Exchange Membrane
AEL	Alkaline Water Electrolysis
SOEC	Solid Oxide Electrolyzer cell
SBC	Sub Bituminous Coal
L	Lignite
DFB	Dual Fluidized Bed
BFB	Bubbling Fluidized Bed
CGE	Coal Gas Efficiency

## 1. Introduction

The transportation industry serves global society by allowing the cross-border movement of both individuals and products. Among the several transportation methods (road, air, and water), road transport is the most convenient since it offers dependable services, such as the movement of goods from the place of origin to the point of delivery. When large numbers of individuals travel by car, air, or train in urban areas, pollution is exacerbated. People like road transit because it allows them to get from their current place to their desired location. The crude oil shortfall has increased considerably in recent years and will likely continue to do so if global economic activity continues. Comparatively, the transportation industry has two sustainability issues: global greenhouse gas emissions and high transportation costs in metropolitan regions. (Global Transport Scenarios 2050, 2011)

Additionally, the high use and consumption of fossil fuels in the transportation sector has increased pollution emissions, resulting in significant negative externalities and environmental damage. These pollutants may include elevated amounts of carbon monoxide (CO), hydrocarbon monoxide (HC), nitrogen oxides (NO<sub>x</sub>), particulate matter (PM), soot, smoke, and carbon dioxide (CO<sub>2</sub>). Transportation produces these gases which can be a source of direct or indirect GHG emissions. Almost all the world's transportation energy (95%) is derived from petroleum-based fuels, namely gasoline and diesel. Emissions are directly related to the amount of fuel consumed in the power and transportation sectors, and it is critical to remember that these pollutants have a detrimental effect on the environment and living circumstances. Indeed, such pollution is detrimental to the ecosystem and may pose risks to human health and well-being. Direct emissions from the transportation sector have been determined to account for 13.5% of global warming. (Global Transport and Climate Change, 2021)

Global warming is accelerating. Year after year, temperatures have risen. One of the primary reasons for this temperature increase is our reliance on non-renewable energy sources such as diesel and petroleum fuel, which emit massive amounts of harmful emissions that contribute to this perilous trend. For decades, diesel fuel has been the preferred fuel for transportation and industry transport services, as well as for regular consumers. This is because diesel engines perform better in demanding applications than spark-ignition engines, and diesel fuel

has a higher power density than other fuels, delivering more power per volume. Diesel fuels, which are refined from crude oil, produce many harmful emissions when burned. Global climate change has finally become the driving force behind the energy sector's expansion since the Paris Agreement was signed. The agreements established the groundwork for consensus goals aimed at slowing and eventually halting global warming. Along with these worldwide ambitions, the European Union (EU) has established goals to cut greenhouse gas emissions by at least 55% by 2030 and to achieve climate neutrality by 2050. (Global Transport Scenarios 2050, 2011)

In 2017, the transport industry accounted for 31% of total energy consumption in Europe, or 326 Mtoe (3797 TWh, 13.67 EJ). Transportation energy consumption continues to be dominated by oil products, with only 8.9 percent of renewable energy used in transportation in 2019. The transport sector accounts for 24% of total EU-28 GHG emissions and 21% of CO<sub>2</sub> emissions. Whereas road transport accounts for 72% of overall transport CO<sub>2</sub> emissions of which passenger cars account for 61%. (Global Transport and Climate Change, 2021)

Green hydrogen, or clean hydrogen, as a renewable source of energy, has the potential to be a game changer in terms of emissions reduction and changing the near future. Environmental assessment to produce green hydrogen is a critical concern for this type of energy fuel.

### 1.1 Research Problem

Globally, there is a sense of urgency about drastically reducing the implications of climate change. Climate change and air pollution are serious problems to humanity, with their causes and solutions inextricably connected. While Europe's air is becoming cleaner, persistent pollution, particularly in cities, continues to harm people's health and economy. Since greenhouse gases and air pollutants are typically emitted by the same source, advantages can accrue by reducing emissions of one or the other. The transport industry consumes over 80% of all oil and petroleum products, and transportation activity is likely to continue growing. By 2050, passenger travel is expected to expand by 42% and freight transport by 60%. If no meaningful change occurs, greater pressure on the environment will follow. (Global Transport and Climate Change, 2021)

Therefore, beginning with the research problem, there are some key factors which have to be taken into consideration. First, do we have an alternate fuel which can replace the conventional fossil fuel in the transportation industry? Secondly, what is the potential of producing them and lastly, what can be the carbon footprints while producing them. In this thesis we will be talking about alternative fuel hydrogen and will be seeing whether it is environmentally sustainable or not.

### 1.2 Objective of work

The goal of this project is to assess the environmental impacts which can be reduced by using green hydrogen as a renewable fuel in the transportation sector. Moreover, the feasibility study will be done between conventional fossil fuel and hydrogen. The aim of the project will be met by doing theoretical analysis of literature review.

### 1.3 Framework

Hydrogen is a versatile element that may be used and harnessed in a variety of ways. It is well-known for its employment in the aerospace sector as a propellant for rockets or for its negative association as a source of bombs. The European Commission's goal is to accelerate the development of clean, renewable hydrogen as a primary decarbonization option in sectors where other alternative fuels can be feasible or expensive. (Hydrogen, n.d.) Green hydrogen is the most frequently used term in this thesis to refer to clean hydrogen created using renewable electricity. In July 2020, the European Commission issued "A hydrogen plan for a climate-neutral Europe." This concept served as the foundation for the development of this master's thesis.

The aim of this thesis is to discuss green hydrogen production and its sustainable impacts on the environment. Also, the benefits of it in the transportation sector over traditional fossil engines would be also discussed in later stages. The research method for the thesis would be done through the literature review and case studies of the European commission and different European countries trying to implement and promote this type of new technology.

### 1.4 Research questions

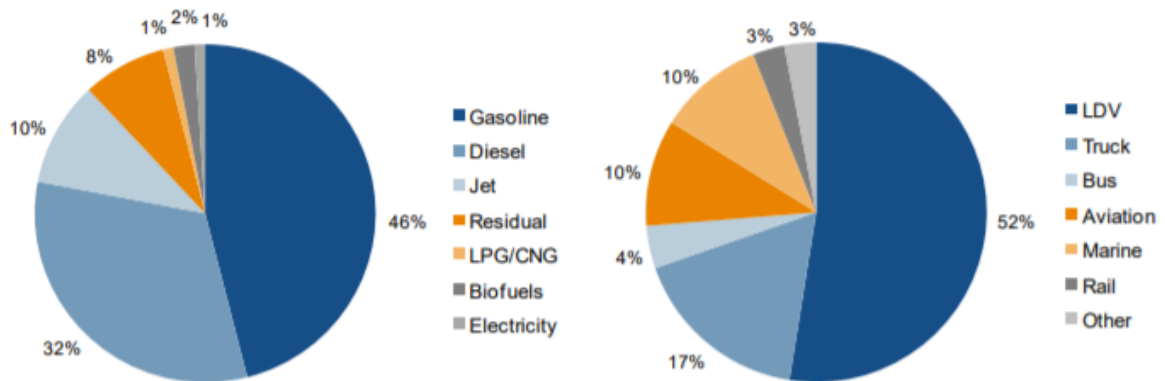
This research is systematically examining the various factors in the transportation sector that are affecting the environment, resulting in dramatic changes in the global atmosphere's

composition and temperature. This research may result in the optimal solution for implementing a new fuel capable of reversing these degradations. This research would try to answer following questions:

1. Why is green hydrogen a better fuel than conventional fossil fuels in transportation?
2. Is it possible to convert all the passenger cars into hydrogen driven?
3. What are the predictions on the future hydrogen production and transport sector in Europe?

## 2. Overview of Global Transport Sector

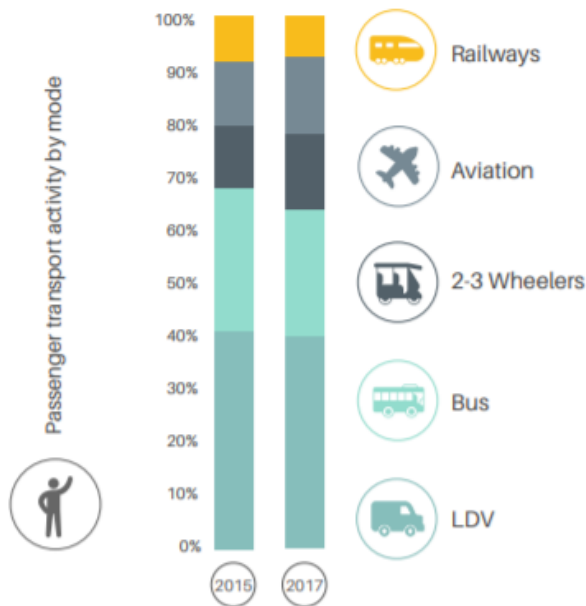
In 2010, the transportation sector was responsible for the use of around 2,200 million tons of oil equivalent (mtoe), which is comparable to approximately 19% of world energy resources. Oil was responsible for around 96 percent of this total, as shown in Figure 1. The remaining four percent came from natural gas, biofuels, and electricity. More than sixty percent of the world's oil consumption, or around fifty one million barrels per day, is put to use in the transportation industry. According to the data presented in the figure, road transportation is responsible for the largest portion (about 76 percent) of the energy consumed by transportation. Trucks, which comprise medium- and heavy-duty vehicles, accounted for around 17% of the total, while light-duty vehicles (LDVs), which include light trucks, light commercial vehicles, and minibusses, accounted for nearly 52% of the total. Full-sized buses accounted for 4% of the remaining road transport share, while two- and three-wheeled vehicles made up the remaining 3%. Railways accounted for just 3% of the overall energy consumption in the transport sector, whereas air and sea transportation together accounted for around 10% of that total. (Global Transport Scenarios 2050, 2011)



**Figure 1.** 2010 transport energy by source and by mode. (Global Transport Scenarios 2050, 2011)

Between 2015 and 2017, the global demand for passenger transportation remained stable at similar levels. In 2017, road transportation accounted for 78 percent of this total demand. In 2017, more goods were moved in trucks than ever before, as cargo activity continued to expand, reaching 120 trillion ton-kilometers for the first time in history. Global passenger

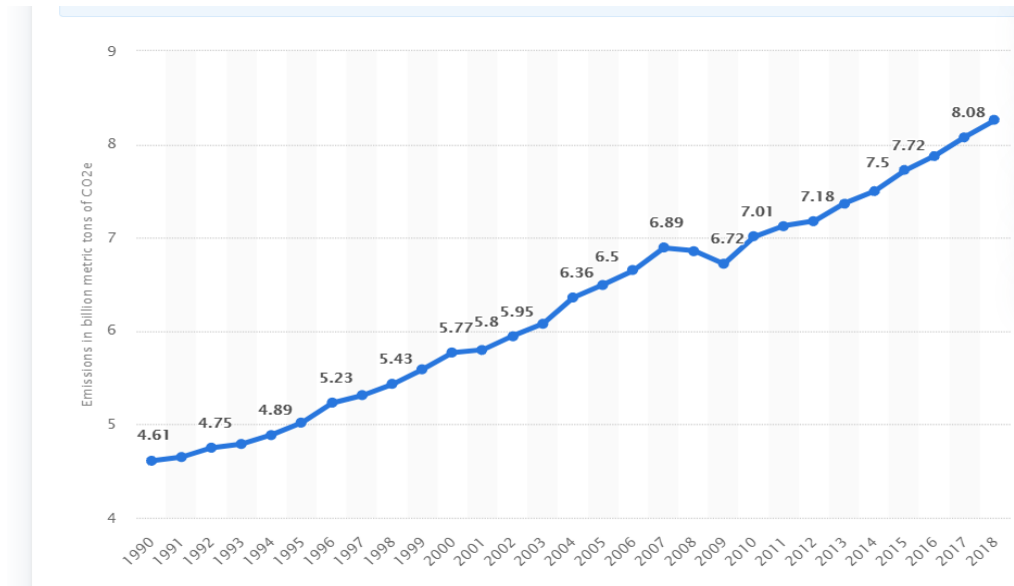
transport activity totaled 55 trillion passenger-kilometers, with road transport accounting for 78 percent of that total. Although rail is by far the most carbon-efficient form of transport, emitting the least CO<sub>2</sub> per passenger, it carried less than 8% of passengers that year. Between 2015 and 2017, the combined growth in passenger transport activities of motorized two- and three-wheelers and aviation were over 25%. (Refer Figure 2). Two- and three-wheelers are indeed the fastest expanding means of motorized mobility in any emerging country. (Global Transport Scenarios 2050, 2011)



**Figure 2.** Share of passenger transport (passenger kilometers) by mode, 2015 and 2017. (Global Transport and Climate Change, 2021)

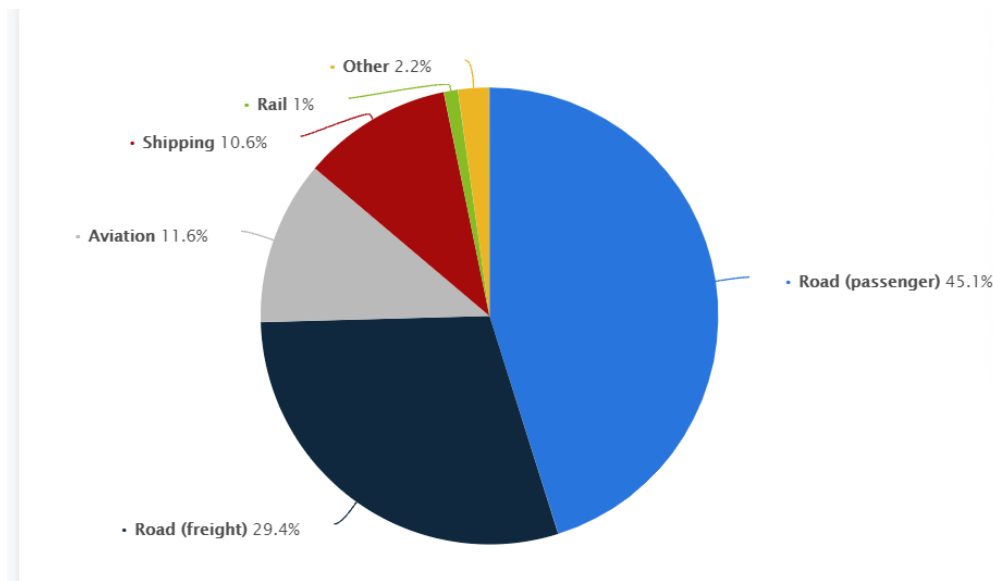
Due to the increase in transport facilities, there was a substantial increase in the global emission trends which affected the environment as whole. Between 2000 and 2018, the expansion of road vehicles (including passenger and freight), aviation, and shipping were the primary drivers of worldwide transportation carbon dioxide (CO<sub>2</sub>) emissions. In 2018, transportation accounted for 14% of total world greenhouse gas emissions. According to Figure 3, road transport accounted for over three-quarters (74%) of that year's transportation greenhouse gas emissions, while rail accounted for only 5%. Around 36% of transportation CO<sub>2</sub> emissions occur in metropolitan areas, with passenger transit accounting for 31.6 percent and freight accounting for 4.7 percent. (Global Transport and Climate Change, 2021)

In 2018, worldwide emissions of greenhouse gases from the transportation industry totaled 8.26 billion tonnes of carbon dioxide equivalent, as reported by the International Energy Agency (IEA). Since 1990, emissions connected to transportation have increased by around 80 percent, with the only major decreases occurring during the worldwide recession in 2009 and 2010. One of the most important sectors responsible for contributing to the release of greenhouse gases is the transportation sector. (Figure 4). (Transport Analysis IEA, 2022)



**Figure 3.** Global GHG emissions from transportation 1990-2018. (Global Transport and Climate Change, 2021)

A major contributor to climate change, especially in arctic regions, black carbon (a short-lived climate pollutant released into the atmosphere because of incomplete fuel combustion) is also a growing public health problem. Fine particulate matter (PM<sub>2.5</sub>) contains a significant amount of black carbon, which can penetrate deep into the lungs, causing premature death as well as a variety of cardiovascular and respiratory ailments in the process. The global emission of black carbon in 2015 was approximately 4,770 gigatons, with road transport accounting for 11 percent of total emissions and all other modes of transportation accounting for 3.5 percent of total emissions in 2015. Approximately 30% of global urban emissions of particulate matter are attributed to road mobility, according to estimates (less than 2.5 micrometers in size). (Global Transport and Climate Change, 2021)

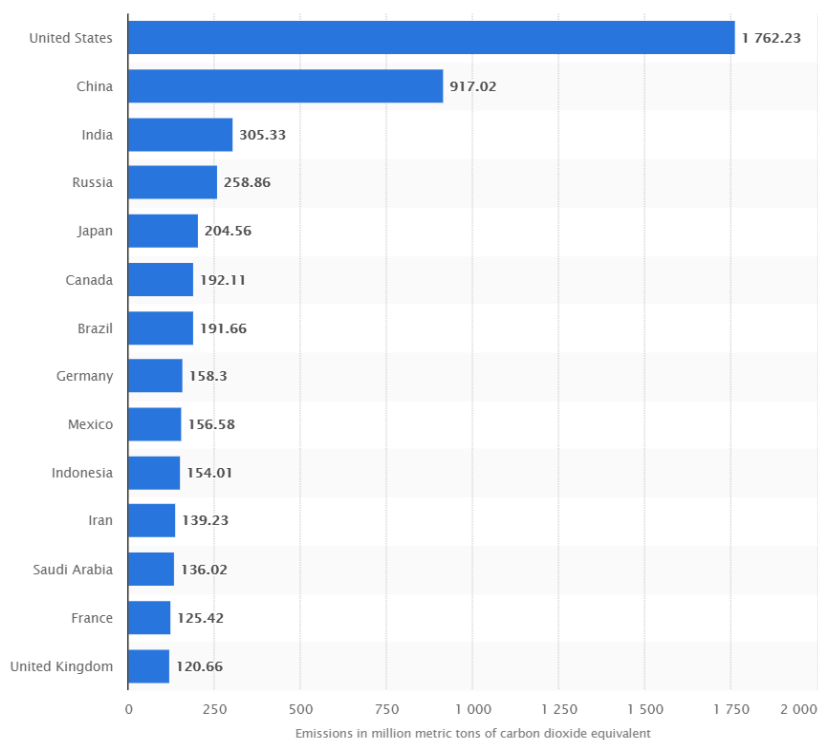


**Figure 4.** CO<sub>2</sub> emissions in the transportation sector worldwide 2018. (Global Transport Scenarios 2050, 2011)

According to some estimates, the global transportation industry generated over 800 million tonnes of CO<sub>2</sub> in 2018, giving it one of the most significant contributors to air pollution. Figure 5 indicates that passenger road transportation, which includes motor cars and buses, were the major contributor that same year, accounting for about 45 percent of all vehicular emissions. Other forms of road transportation, such as freight transportation, accounted for the remaining 55 percent. It is estimated that road transportation is responsible for around 14 percent of the total world emissions of greenhouse gases. (Global Transport Scenarios 2050, 2011)

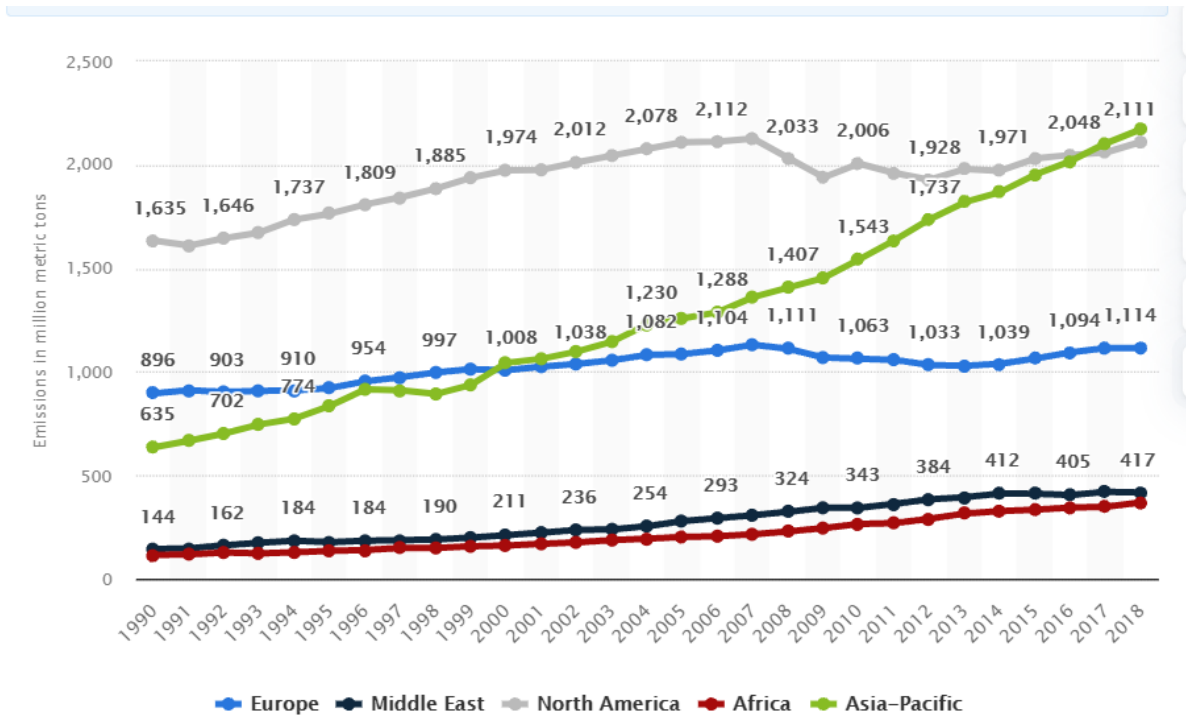
The United States of America is one of the major world's leading producers of transportation emissions, emitting 1.76 equivalent billion metric tons of CO<sub>2</sub> in 2018. In terms of transportation emissions, this was almost similar to the total emissions from China, India, Russia, and Japan combined. The United States has one of the highest per capita levels of emissions from road transportation in the world. In 2018, the average American released approximately 4,500 kg of CO<sub>2</sub> through road transportation, which was somewhat higher than the average Canadian in the same year. The US is the world's leading emitter of CO<sub>2</sub> emissions from road transportation, followed by China and the European Union (See Figure 6). China, on the other hand, has significantly lower emissions per capita than the United States. Reduced road transportation emissions per capita are significantly lower in

low-income nations, such as those in South Asia and Africa, compared to higher-income countries. For example, in 2018, Eritrea's per capita road transportation emissions totaled 63 kg CO<sub>2</sub>/capita, according to the World Bank. This was nearly 70 times lower than the per capita emissions in the United States of America (USA). (Global Transport and Climate Change, 2021)



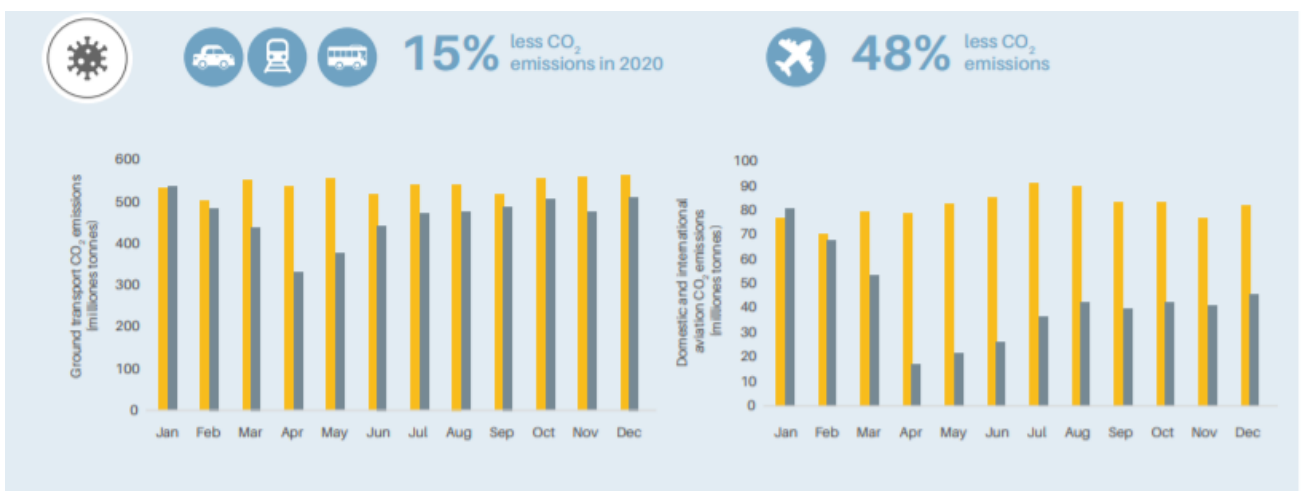
**Figure 5.** Global GHG emissions of major countries in the transportation sector 2018 (Global Transport and Climate Change, 2021)

In the previous three decades, North America has emerged as the world's top producer of CO<sub>2</sub> from the transportation industry. In recent decades, emissions from the transportation sectors of Europe and North America have slowed or even declined, whilst emissions from emerging countries such as Africa have increased dramatically. As the country's economies continue to expand, emissions in Asia-Pacific have climbed by more than 200 percent. (Refer to Figure 7).



**Figure 6.** CO<sub>2</sub> emissions worldwide from 1990-2018 (Global Transport and Climate Change, 2021)

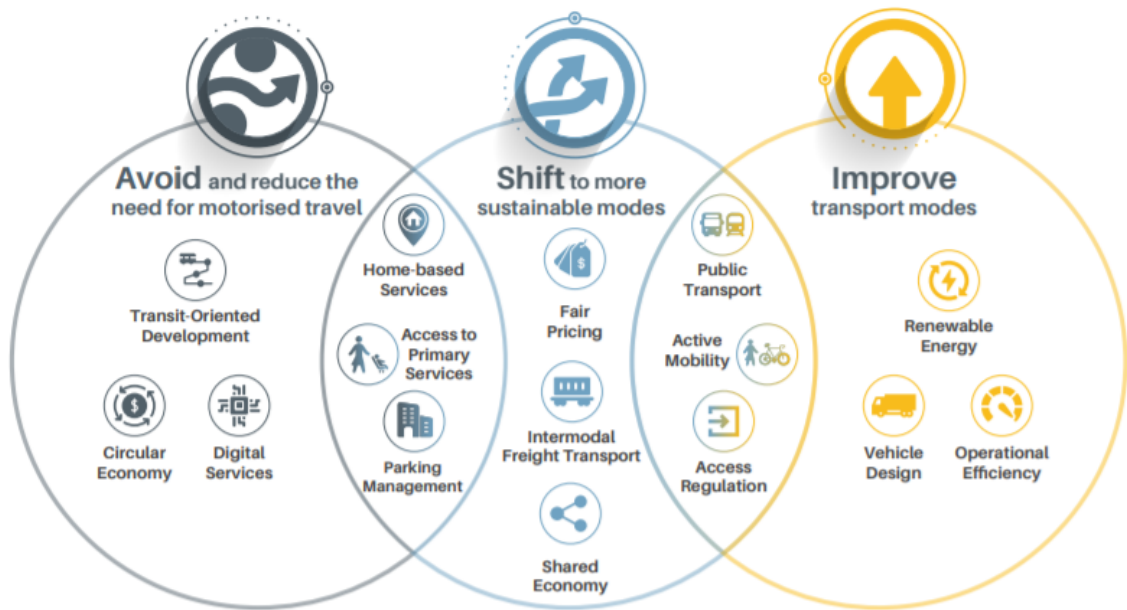
There was a decline in the emission trends due to COVID-19 impact. It was seen as beneficial for the environment due to decrease in mobility. Transport related CO<sub>2</sub> emissions decreased by 1.5 gigatons in 2020. Worldwide energy demand fell by 4%, while overall global CO<sub>2</sub> emissions fell by 5.4 percent. The fall in emissions is primarily due to the fast decline in aircraft and road transport activities during the pandemic's early months.



**Figure 7.** COVID-19 impacts on CO<sub>2</sub> emissions from land transport and domestic aviation. (Global Transport and Climate Change, 2021)

CO<sub>2</sub> emissions in the transport industry decreased by 19.4 percent in 2020, with emissions falling by 56.4 percent in international aviation, 31.9 percent in domestic aviation, 24.8 percent in international shipping, and 14.6 percent in ground transport (road and railways). Total emissions from land transportation decreased by approximately 947 million tonnes of CO<sub>2</sub>, while domestic and international aviation emissions decreased by approximately 466 million tonnes of CO<sub>2</sub> (See Figure 8). The epidemic of COVID-19 resulted in a 14.5 percent decline in new car sales, from 91 million in 2019 to 78 million in 2020. In summary, the COVID-19 pandemic exposed the transportation sector's vulnerability to calamities and global shocks. In several cities, public transportation systems were on the edge of collapse in 2020, as ridership, revenue, and passenger trust all declined significantly. However after the pandemic mobility emissions have started to increase rapidly with transportation returning to its normal phase. (Global Transport and Climate Change, 2021)

The policies play a vital role in deciding the parameters affecting the mobility sector. There have been various policies implemented by different governments in different regions. One well known sustainability approach is done by applying the Avoid-Shift-Improve (ASI) approach. It is quantified using integrated, multimodal, and balanced methodologies, which are necessary for maximizing the benefits of sustainable, low-carbon transportation. For more than a decade, the A-S-I structure has been important to sustainable, low-carbon transportation. The A-S-I strategy is implicitly hierarchical, employing suitable and context-sensitive terminology. Avoidance measures are designed to be adopted initially, followed by Shift, and Improve actions. This prioritization can assist in reducing environmental impact, increasing socioeconomic opportunity access, increasing logistical efficiency, reducing congestion, improving air quality, and increasing road safety. Figure 9 represents the ASI approach Framework. (Global Transport and Climate Change, 2021)



**Figure 8.** ASI approach framework. (Global Transport and Climate Change, 2021)

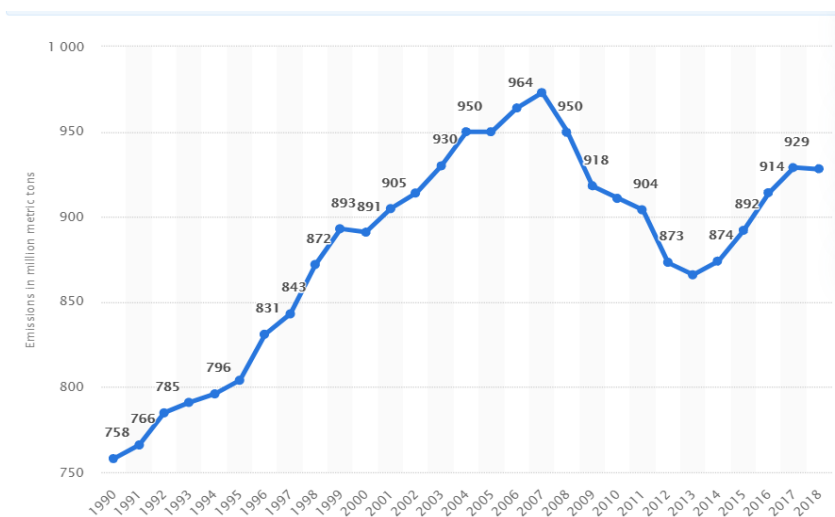
Avoid and Shift strategies can account for 40-60% of transportation emission reductions at a lower cost than Improve techniques, according to growing data. There is widespread recognition that present policies rely excessively on technology-focused improvement initiatives and so fall short of the systemic and rapid transformation required to reach global climate and equality goals. Countries updated Nationally Determined Contributions (NDCs) to reduce emissions under the Paris Agreement continue to place a premium on Improve initiatives, which account for 52% of all measures, compared to 38% for Shift measures and 10% for Avoid measures. Given the long-term consequences of some Avoid and Shift policy initiatives, it is critical that countries' Nationally Determined Contributions and Long-Term Climate Strategies have a balanced A-S-I approach. However, an excessive emphasis on improvement methods, particularly vehicle electrification, risks diverting attention away from critical long-term structural changes, modifications to business models, supply chains, urban planning, and behavior. (Global Transport and Climate Change, 2021)

## 2.1 Overview of Transport sector in Europe

When it comes to the issue of pollution in the European Union, one of the primary contributors is the transportation sector. This sector is responsible for the emission of significant quantities of greenhouse gases in addition to common pollutant contaminants such as nitrogen dioxide. During the same time period, emissions from other industries, such as the

energy sector have significantly decreased, on the other hand, emissions from the transportation industry have increased, putting it as the second worst polluting industry in the EU. In the year 2019, the transport sector was responsible for producing emissions that were equivalent to 1.1 billion metric tons of CO<sub>2</sub>. It was the sixth year in a succession that transportation-related emissions increased, and it represented a 33 percent growth when compared to the levels that existed in 1990. In spite of the overall upward trend in emissions, it is anticipated that the travel restrictions imposed by the beginning of COVID-19 will have a large effect on transportation emissions in the year 2020. As a result, emissions from this sector are expected to decrease by approximately 19 percent in some of the countries that make up the EU. (Carlier, 2022)

The emissions of carbon dioxide produced by the transport industry in the European Union increased from 758 million tonnes to 973 million tonnes during the course of the twenty years that span between 1990 and 2007. In the years that followed, reductions were observed, and by 2013, the total quantity of carbon dioxide that had been emitted had dropped to 866 million tonnes. Since that time, however, emissions from transport have climbed, with a total of 982 million tonnes of carbon generated in 2018, making it one of the major contributors to environmental pollution in the EU. (Carlier, 2022)



**Figure 9.** CO<sub>2</sub> emissions in the European Union from 1990-2018. (Carlier, 2022)

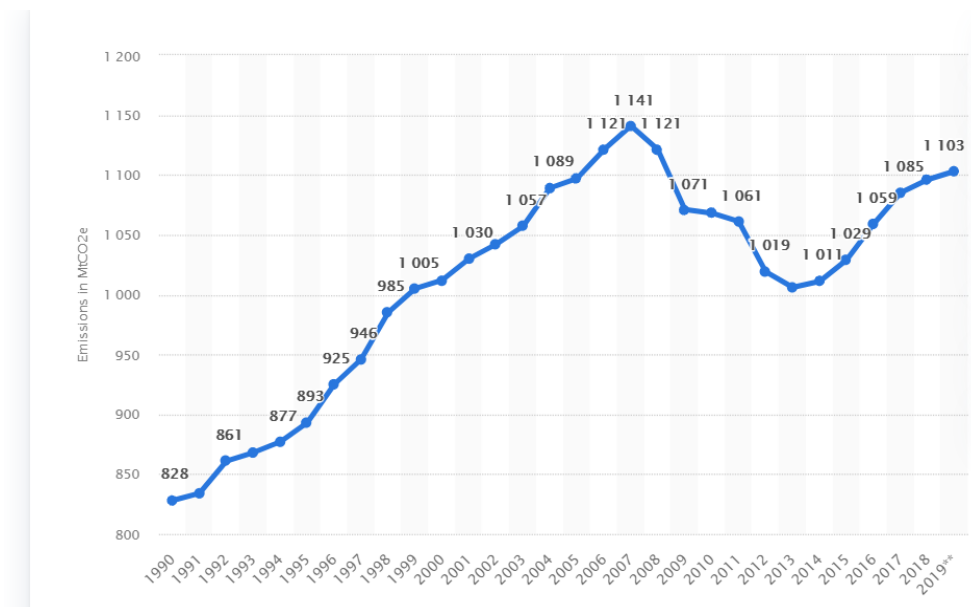
Since 2014, the quantity of greenhouse gas emissions produced by the transport industry in the EU-28 has increased slowly but steadily. This sector excludes maritime transportation.

Compared to 2016, 2017 emissions increased by 2.2%, with the majority of the increase attributable to an increase in road transportation emissions, followed by an increase in aircraft emissions. According to figures released by the European Commission in 2017, air travel and shipping accounted for 27% of the EU-28's total emissions of greenhouse gases. Excluding foreign transportation from the equation, the proportion decreases to 22%. In 2018, according to data provided by the European Environment Agency (EEA), emissions from transport, including aircraft, increased by 0.7%. In 2017, road transportation was accountable for more than 72 percent of the total transport industry greenhouse gas emissions (including international aviation and international shipping). These emissions were produced by passenger cars at a rate of 44%, light commercial vehicles at a rate of 9%, and heavy-duty trucks and buses at a rate of 19%. (Carlier, 2022)

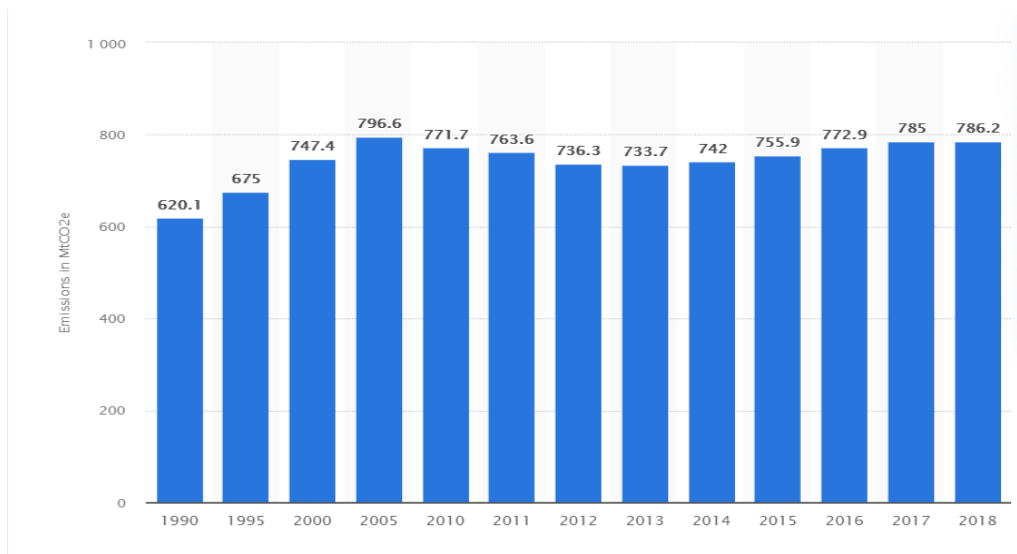
In 2018, emissions from newly registered passenger vehicles hit a record high of 120,4 grams of carbon dioxide per kilometer. This is the second consecutive year when particular emissions have risen. After a 22 gCO<sub>2</sub>/km fall from 2010 to 2016, the average emissions of new passenger automobiles climbed by 0.4 gCO<sub>2</sub>/km in 2017. Initial data indicate that the rising trend persisted throughout 2018, with a further 2.0 gCO<sub>2</sub>/km rise reported over the year. One of the most significant factors to the growth in emissions from brand-new passenger vehicles in 2018 was the increase in the number of new registrations for gasoline-powered vehicles, particularly sport utility vehicles. (Carlier, 2022)

In the European Union in the year 2018, gasoline-powered passenger cars were the most widely purchased vehicles, accounting for almost 60% of total sales in the region (up from 53 percent in 2017). 36 percent of all new passenger cars registered were diesel-powered automobiles (95 percent for new vans). In 2018, the market penetration of zero-emission and low-emission cars, such as electric vehicles, remained low. This is consistent with the results of prior years. It is imperative that we expedite the distribution of low-emission automobiles across Europe in order to meet the imminent goal of 95 gCO<sub>2</sub>/km in 2021. The CO<sub>2</sub> emissions produced by new vans have, for the very first time, shown a year-over-year increase over the same period. According to early findings, the average amount of carbon dioxide released into the atmosphere by vehicles in 2018 was 2 gCO<sub>2</sub>/km more than the same time in 2017. Following a considerable drop the year before to the legislation's implementation in 2011, this is the first year that there has been a rise since the legislation was put into force. Between the

years 2012 and 2018, average specific emissions went down by 22 gCO<sub>2</sub>/km, which is equivalent to a 12 percentage point decrease in emissions overall. According to Figure 11, 1.1 million metric tons of carbon dioxide were emitted by the transportation sector in the European Union in the year 2019. Since 2013, annual increases in emissions from transportation have been observed. In the European Union, road traffic is the most significant source of transportation emissions. Whereas, as a result of road transportation in the European Union (EU-27), 786 million metric tons of CO<sub>2</sub> were emitted during 2018 (see Figure 12). Despite a drop in emissions between 2005 and 2013, emissions have increased on a yearly basis since 2013. (Transport Statistics at Regional Level - Statistics Explained, 2022)

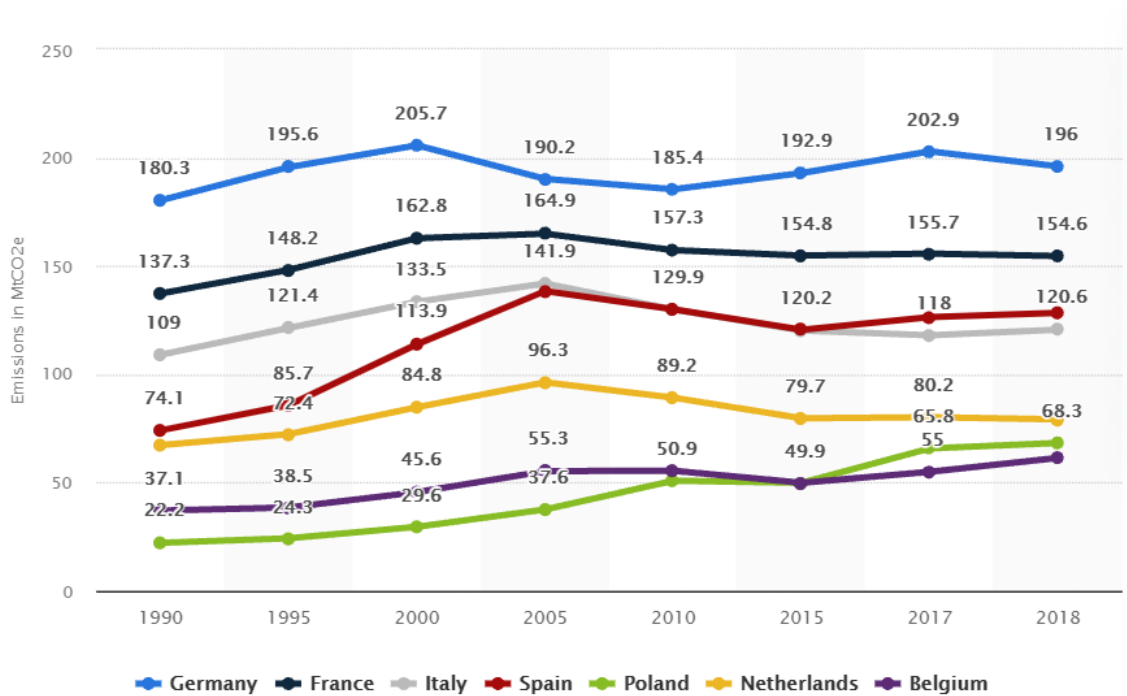


**Figure 10.** GHG emissions in the EU from 1990-2018. (Transport Statistics at Regional Level - Statistics Explained, 2022)



**Figure 11.** GHG emissions from road transportation in the EU during 1990-2018. (Carlier, 2022)

With emissions equivalent to 194 million metric tons of carbon dioxide in 2018, Germany ranks first among all countries in the European Union in terms of transportation-related emissions. France and Italy, with emissions of 150 and 116 million metric tons carbon dioxide equivalent, respectively, were in second and third place, respectively. Germany has continuously ranked first in the European Union in terms of emissions from transportation-related activities. Between 1990 and 2018, Germany's transportation emissions (which include international bunkers) grew by around nine percent, reaching 196 million tons of carbon dioxide equivalent. Even though Poland's transportation-related emissions are significantly lower than those of other EU countries, they have climbed significantly during the past 30 years. Polish transportation emissions were 22.2 million metric tons of carbon dioxide equivalent in 1990, but by 2018 they had increased to 68.3 million metric tons of carbon dioxide equivalent, making the country one of the EU's top polluters in this sector. (Refer Figure 13) (Carlier, 2022)



**Figure 12.** GHG emissions from transport in the EU-27 during 1990-2018. (Carlier, 2022)

In the European Union during 2018, road transportation was responsible for around 72 percent of all greenhouse gas emissions caused by transportation related activities (See Figure 14). In accordance with the European Commission, passenger vehicles accounted for the most substantial source of GHG emissions in the EU during 2019, associated with road transportation. Passenger automobiles were responsible for more than 60 percent of the overall greenhouse gas emissions generated by the transport sector in the European Union . The second largest contributor to emissions from the transport sector were heavy-duty vehicles and buses, which are responsible for around 27 percent of the overall emissions. Since 1990, when passenger vehicles produced 381 million metric tonnes of CO<sub>2</sub>, they have continuously been the most major source of emissions produced by road transportation in the European Union. As of the year 2018, vehicle emissions had increased by around 25 percent, reaching 469 million metric tons. (See Figure 15). (Carlier, 2022)

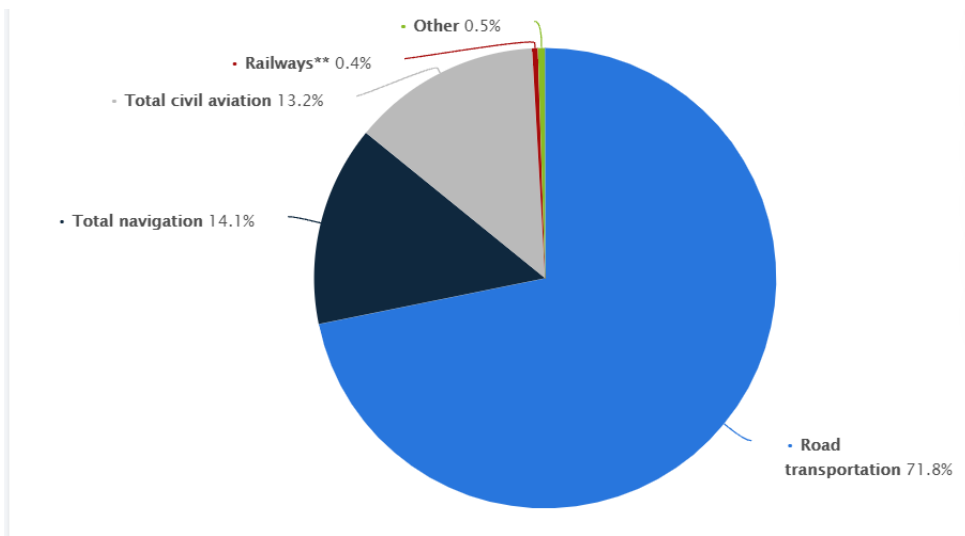


Figure 13. Breakdown of transportation GHG emissions in the EU . (Carlier, 2022)

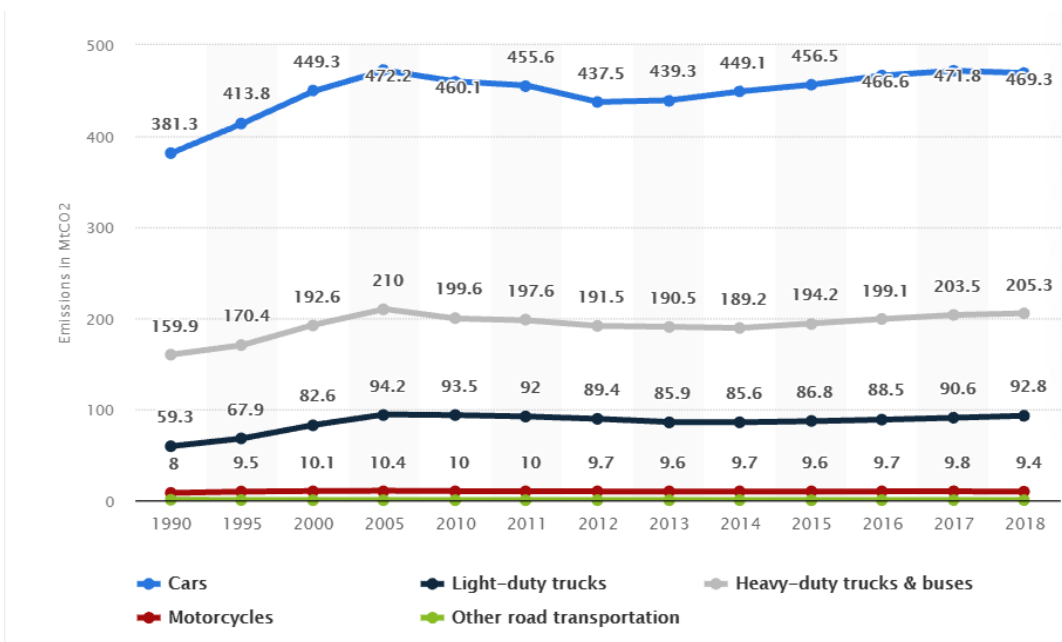


Figure 14. CO<sub>2</sub> emissions due to roads in the EU during 1990-2018. (Carlier, 2022)

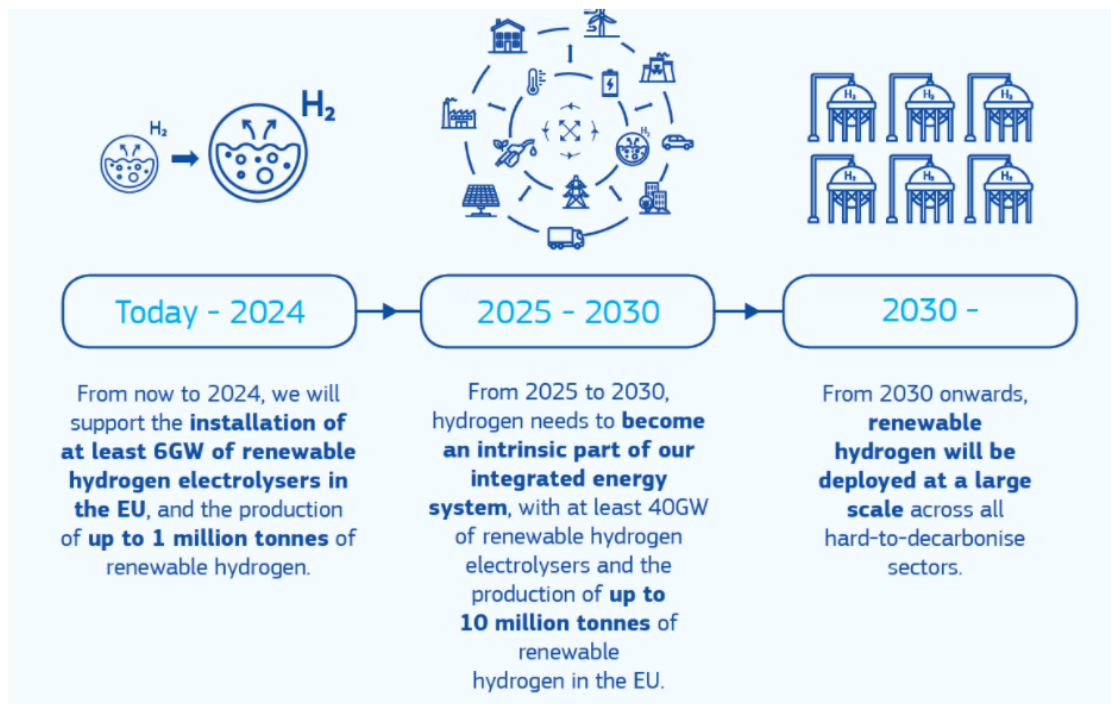
### 3. Green Hydrogen Production

#### 3.1 Green Hydrogen as a future fuel

Hydrogen is the most common and lightest element in the universe; its atoms only contain one proton and neutron respectively. Hydrogen is the most plentiful element. The most common component containing hydrogen is water, while it is present in a wide range of other substances as well. One of the most significant benefits of utilizing hydrogen is that it may help reduce emissions, which is one of the chemical element's key advantages. As a consequence of this, hydrogen possesses an enormous potential to make a large contribution to the ongoing energy revolution throughout the world and to play an important part in the process of reducing emissions. Different energy sources can be used to generate hydrogen, which can be created in a variety of ways. The usage of hydrogen in and of itself does not result in harmful emissions, but when classifying hydrogen into different categories, it is important to consider the technique of hydrogen synthesis. When hydrogen is produced using water electrolysis and the procedure is driven by renewable energy, it is referred to as "green hydrogen." However, the most widely used hydrogen generation technologies today are not environmentally benign because they rely on fossil fuels, resulting in the production of grey hydrogen. Blue hydrogen indicates hydrogen generated in a manner like that of grey hydrogen, except in which carbon has been trapped and held instead of being released. (Mäkelä, 2021)

In the future, the European Union plans to make considerable cuts to the amount of carbon dioxide that is released during the production of hydrogen, with the ultimate goal of achieving carbon-free manufacturing. At this time, the generation of hydrogen in the EU is responsible for the annual release of between 70 and 100 million tons of carbon dioxide into the atmosphere. According to the Environmental Protection Agency (2018), the average passenger car run on gasoline, produces 4.6 tons of CO<sub>2</sub> over the course of one year. As a result, the production of hydrogen in the EU is comparable to the annual CO<sub>2</sub> emissions of 15-22 million passenger vehicles per year.. Because of the emissions that are linked with the current generation of hydrogen, green and blue hydrogen are the key options that are being taken into account in the recovery plan and hydrogen strategy that is being developed by the European Commission. In every one of these hypothetical situations, the objectives are quite lofty, with the years 2030 and 2050 being brought up as reference points the vast majority of

the time. The European Union (EU) aims to achieve one of its most ambitious goals by the year 2030, which is to have an electrolyzer potential of 40 GW. This is the key objective. It is anticipated that the amount of hydrogen generated by electrolyzers will significantly expand in the near future. The fact that the total electrolyser capacity in Europe is somewhere near 1 GW, the estimates of the impact of green hydrogen both economically and socially will be highly variable from one scenario study to the other. For instance, in accordance with the European hydrogen strategy, the total investments necessary for increasing the use of environmentally friendly hydrogen might range anywhere from 180 billion euros to 470 billion euros over the course of the following ten years. (Tasić, 2021)



**Figure 15.** The Hydrogen Path in the EU. (Tasić, 2021)

Figure 15 was given by Trinomics (2020), in their study on the various technologies related to hydrogen, which can be viewed here, it mainly illustrates how the 28 countries that make up the European Union are likely to be affected economically and socially as a result of the development of environmentally friendly hydrogen technologies. The problem becomes more difficult when the values are scaled to reflect the size of each country. For illustration purposes, when the demand for environmentally friendly hydrogen is weighed against the size of the population, Finland has the greatest demand per individual (0.91 MW). The steel industry in Finland, which has a substantial potential for increased hydrogen consumption,

can be regarded as a significant single component despite the fact that a number of other variables are also contributing to this phenomenon. It is possible to ascertain, via the utilization of a comparative method of a similar kind, that the Netherlands has the second highest demand per inhabitant (0.69 MW). According to the findings as a whole, green hydrogen is anticipated to be a feasible alternative for decarbonization of the energy industry across the European Union. This prediction comes from the findings. In terms of size, the results in Germany are located on an entirely different scale than those in any of the other nations that are members of the EU. The same statistic leads one to the same conclusion: in the not-too-distant future, Germany will have the hydrogen economy that is the most developed in all of Europe. Germany will have the highest levels of demand, electrolysis capacity, added value, jobs produced, and averted consumption of fossil fuels. Additionally, Germany will have the highest quantity of fossil fuel use that will be avoided. The European Union (EU) has a significant opportunity to expand its hydrogen markets if it makes full use of the advantages that come naturally to the region. It is essential that the European Union (EU) fulfills its potential as a dominating participant in the hydrogen and fuel cell value chain in the years to come. This potential must be fully fulfilled. The European Union currently possesses an extremely wide gas network that has the potential to be utilized in the manufacturing of hydrogen. (The Study “Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans” Has Just Been Published!, 2020) (Mäkelä, 2021)

Member State	Hydrogen demand (TWh <sub>H2</sub> /a)	Electrolysis capacity in GW <sub>el</sub> (SMR+CCS capacity in GW <sub>H2</sub> ) <sup>2</sup>	Avoided fossil fuel imports (TWh/a)	Value added (million EUR)	Jobs (FTEs)
Austria	2 - 6	0.6 - 2.0	4 - 11	303 - 980	3324 - 10509
Belgium	1 - 7	0.4 - 2.3	2 - 8	224 - 1140	2525 - 10735
Bulgaria	0.8 - 1.4	0.3 - 0.5	1 - 2	109 - 190	3354 - 6001
Croatia	0.1 - 0.4	0.03 - 0.2	0.1 - 1	13 - 70	177 - 591
Cyprus	0.02 - 0.1	0.01 - 0.1	0.03 - 0.1	5 - 30	97 - 599
Czech	0.4 - 2	0.1 - 0.6	1 - 3	77 - 290	535 - 1330
Denmark	0.4 - 2	0.1 - 0.6	1 - 2	66 - 290	558 - 1442
Estonia	0.01 - 0.1	0.005 - 0.05	0.03 - 0.2	2 - 20	70 - 483
Finland	1 - 5	0.3 - 1.1	3 - 11	273 - 900	2728 - 8854
France	4 - 20	1.2 - 5.3	8 - 27	669 - 2680	10379 - 33648
Germany	9 - 41	3.0 - 13.7 (1.1 - 5.0)	19 - 67	1918 - 7620	23192 - 82799
Greece	1 - 3	0.4 - 1.0	2 - 4	229 - 540	4450 - 10432
Hungary	1 - 2	0.3 - 0.9	1 - 3	134 - 360	721 - 1548
Ireland	0.1 - 1	0.0 - 0.3	0.2 - 1	15 - 130	246 - 1797
Italy	4 - 20	1.3 - 6.7	7 - 26	779 - 3510	11509 - 41760
Latvia	0.05 - 0.2	0.02 - 0.1	0.1 - 0.3	8 - 30	316 - 1222
Lithuania	0.1 - 0.7	0.04 - 0.3	0.1 - 1	18 - 120	569 - 3742
Luxembourg	0.1 - 0.4	0.1 - 0.3	0.2 - 1	44 - 160	420 - 1531
Malta	0.01 - 0.05	0.003 - 0.03	0.01 - 0.04	1 - 10	33 - 224
the Netherlands	3 - 12	0.8 - 3.6 (0.3 - 1.5)	4 - 14	460 - 1930	5112 - 18204
Poland	2 - 6	0.7 - 1.7	3 - 8	343 - 870	3597 - 8608
Portugal	1 - 7	0.3 - 2.7	1 - 8	92 - 740	2500 - 18450
Romania	1 - 2	0.3 - 0.8	2 - 3	156 - 350	1925 - 4440
Slovakia	0.4 - 1.1	0.1 - 0.4	1 - 2	59 - 160	1285 - 3609
Slovenia	0.1 - 0.2	0.02 - 0.1	0.1 - 0.3	12 - 30	270 - 686
Spain	4 - 17	1.0 - 4.1	7 - 20	604 - 2360	10527 - 35827
Sweden	2 - 5	0.4 - 1.2	4 - 11	312 - 880	1106 - 2593
UK	4 - 21	1.1 - 5.6 (0.5 - 2.5)	7 - 27	664 - 2940	12532 - 45975
<b>EU28</b>	<b>42 - 183</b>	<b>13 - 56 (1.9 - 8.9)</b>	<b>80 - 259</b>	<b>7 590 - 29 330</b>	<b>104 060 - 357 630</b>

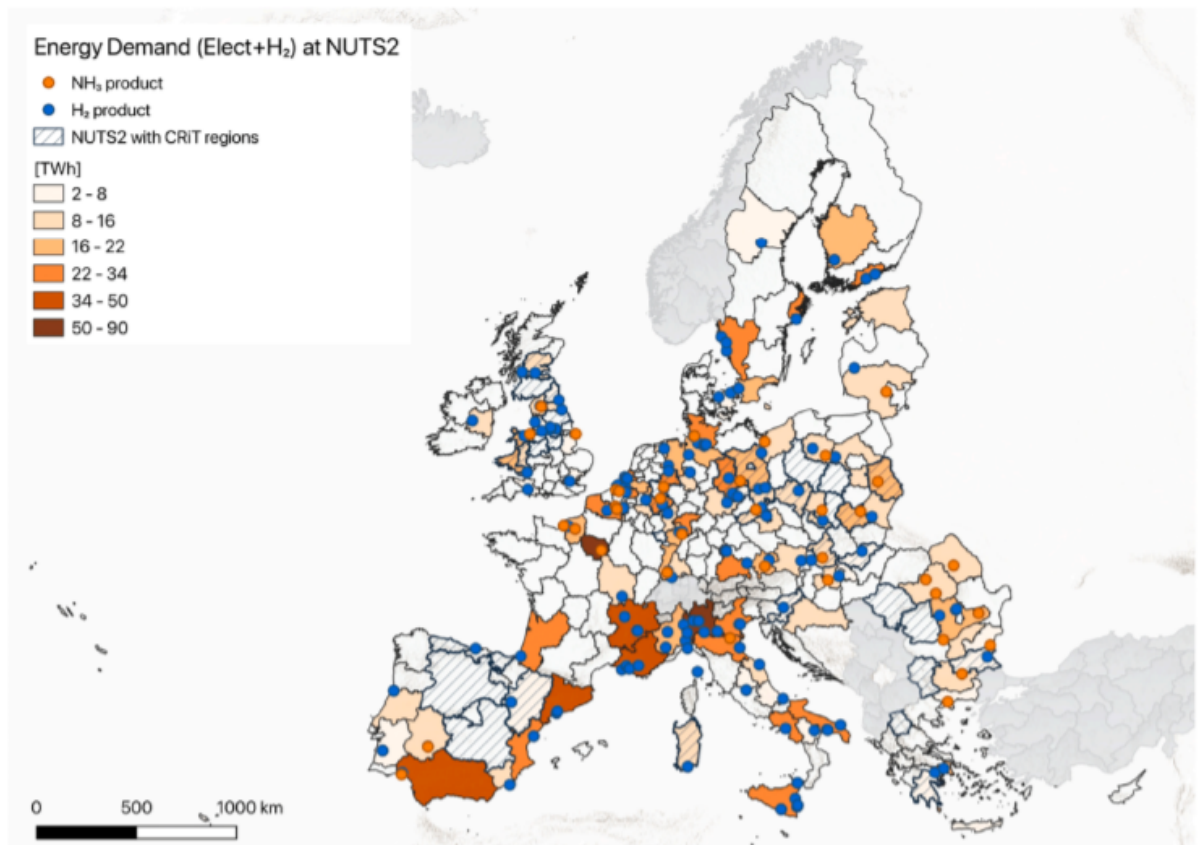
**Figure 16.** Prediction of H<sub>2</sub> demand of the countries in the EU. (Mäkelä, 2021)

Approximately 120 Mt of hydrogen are created annually on a global scale, with two-thirds being pure hydrogen and one-third being a combination of other gases. Natural gas and coal are responsible for approximately 95% of all hydrogen generation. As a byproduct of the electrolysis process used to manufacture chlorine, approximately 5% of the chlorine is produced. Coke oven gas, which is utilized in the iron and steel industry, contains a high concentration of recoverable hydrogen. Currently, a significant amount of hydrogen may be created from renewable sources. Depending on the technology and energy source employed to

make hydrogen, a wide range of pollutants can be generated through a number of production methods. Renewable hydrogen is created through electrolysis using renewable energy sources (RES). Renewable hydrogen has the potential to be the most compatible option with the EU's climate neutrality goal due to its strong decarbonization potential. The majority of the cost of producing green hydrogen is dictated by the capital expenditures for the electrolyzer, the utilization factor (the number of hours the electrolyzer is in operation), and the cost of electricity. (MSc Program Environmental Technology & International Affairs Hydrogen as a Potential Renewable and Secure Source for Energy Supply, 2019)

By subtracting the amount of power needed to meet the present total electricity consumption across all sectors in each country or area, as assessed by the International Energy Agency, this scientific technique compares the prospective electricity demand for transitioning to green hydrogen industrial production with the renewable energy potentials (solar, wind, and hydro). This comparison is carried out in order to ascertain whether or not the prospective supply of renewable energy sources is capable of satisfying the potential demand for power (solar, wind, and hydro). The purpose of this research is to determine whether or not it is possible to make the switch to the generation of green hydrogen in industrial settings. A total of approximately 9.756 million metric tons (Mt) of hydrogen is generated each year in Europe for use in various applications (merchant hydrogen and purposely produced hydrogen, and not hydrogen produced as a by-product). The production of ammonia (which accounts for roughly 43% of total consumption) and oil refining (which accounts for approximately 52% of total consumption) are the two businesses that account for the great majority of hydrogen use. Figure 18 demonstrates that suitable hub sites often take the form of refineries, which contain specific hydrogen generating units and ammonia manufacturing plants. In the second scenario, industry standards require that pure hydrogen also be created and utilized at a rate of around 17 percent by weight per unit of ammonia production. This requirement applies to both of the previous scenarios. The amount of ammonia that is generated serves as the basis for this consumption rate. As can be seen in Figure 16, the amount of hydrogen that was produced geographically accounted for 68% of the total that was forecasted to be produced annually in both the European Union and the United Kingdom. If we were to make a comparison, this would be equivalent to 290 terawatt hours of hydrogen or 6,626.2 tonnes of carbon dioxide (73.7 billion m<sup>3</sup>). The electrolyser technology that is employed may have a significant impact on the amount of energy that is required to convert electricity into

hydrogen. Additionally, this electrolyser technology is continually being researched and developed further. In comparison, the amount of energy that is used by proton exchange membrane (PEM) electrolysers may vary anywhere from 55 to 58 kWh/kg, while the amount of energy that is used by solid oxide electrolysis (SOE) can range anywhere between 40 and 41 kWh/kg<sup>3</sup>, respectively. The amount of energy required to produce one kilogram of alkaline electrolyte is between 50 and 51 kWh. For the purpose of this study, the intended outcomes were achieved by combining lowered heating values with an electrolyser efficiency of 48 kWh/kg<sup>4</sup>, respectively (LHV). As a direct result of this, Germany is the nation that has the highest need for energy for electrolysis (102.8 TWh), followed very closely in second place by the Netherlands (102.8 TWh) (74 TWh). (Thomson, 2021)



**Figure 17.** Distribution of hydrogen production hubs in the EU. (Thomson, 2021)

Source	Annual H <sub>2</sub> production*	
	kt	bn m <sup>3</sup>
Hydrogen Roadmap Europe 2015	9 756	109.5
Chemical industry database	8 716	97.2
of which pure H <sub>2</sub> (not geo-located)	2 090	23.5
of which pure H <sub>2</sub> (geo-located)	2 886	32.1
of which H <sub>2</sub> for NH <sub>3</sub> production (geo-located)	3 740	41.6

\*-Standard Ambient Temperature and Pressure (SATP), Standard ambient temperature is 25 °C, Standard pressure is 1 bar.

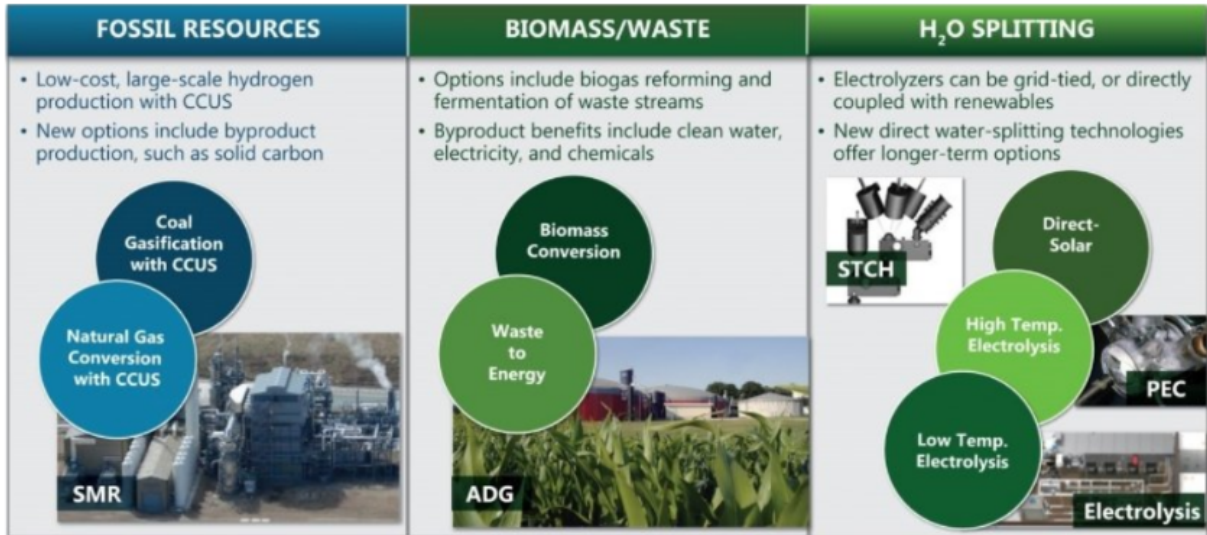
**Figure 18.** EU27 + UK hydrogen production. (Thomson, 2021)

The use of renewable energy sources (RES) at large proportions as a means of meeting the demand for power is an essential component of attempts to achieve net zero carbon emissions and mitigate climate change. It is imperative that any initiatives aimed at producing green hydrogen through the utilization of processes that are powered by renewable electricity be powered by renewable electricity if these initiatives are to avoid having a negative impact on the transition to clean electricity generation systems. Figure 18 is a representation of the computed power demand across all industries for the year (2019) at the regional level. This demand takes into account both the current consumption and demand of hydrogen that is produced through the electrolysis of water, as well as the demand for hydrogen in the future. (Thomson, 2021)

### 3.2 Hydrogen Production

Hydrogen may be created from a variety of widely available materials on a household basis. In addition to carbon capture and storage technologies, fossil fuels such as coal and natural gas might be converted into hydrogen. Utilizing carbon collection, use, and storage technology, it is feasible to lessen the carbon footprint of these operations. In addition to fossil fuels, hydrogen may be created from low-carbon and renewable resources such as biomass extracted from crops not intended for human use and the splitting of water utilizing renewable energy sources such as wind, solar, geothermal, nuclear, and hydroelectric power. Additional possible sources of hydrogen include microbial fuel cells and saltwater electrolysis. Large central facilities, smaller semi-central facilities, and even smaller scattered units are all capable of producing hydrogen near or very close to the point of consumption, such as refueling stations or stationary power plants. This is in addition to the already-established

massive central facilities. The amount of energy contained in 3.78 liters of gasoline is equal to one kilogram of hydrogen. (U.S Department of Energy, 2016)



**Figure 19.** Hydrogen production processes. (U.S Department of Energy, 2016)

Hydrogen can be produced through various different technologies and still the research is going on on newer environmentally friendly techniques. Most of the processes used nowadays produce “gray or blue hydrogen”. Although, in order to produce greater green hydrogen, electrolysis is one of the key techniques at the moment. The research is going on how to increase the efficiency of these techniques, few of the available processes are discussed below.

### 3.2.1 Natural Gas Reforming

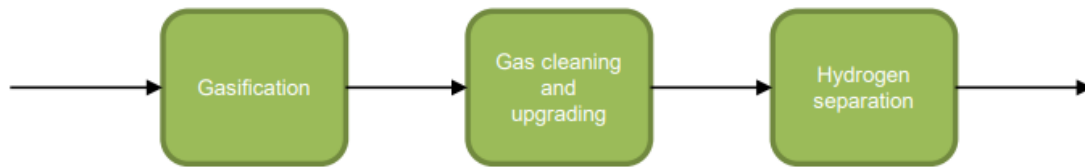
One technique for obtaining hydrogen from natural gas to be utilized in industrial processes is by using steam heated to extremely high temperatures. A technique known as steam methane reforming is responsible for the creation of around 95 percent of the hydrogen used in the United States today. Partial oxidation, which includes the burning of methane in the presence of oxygen, can also result in the production of hydrogen. Either steam reforming or partial oxidation can be used to convert carbon monoxide and hydrogen into synthesis gas, which can then be reacted with additional steam to generate a gas stream with a greater concentration of hydrogen. Synthesis gas is often referred to as syngas. At high temperatures (1,300–1,800 degrees Fahrenheit) and pressures ranging from 3 to 25 bars (1 bar = 6.577

kilograms per square inch), the reaction between methane and steam necessitates the use of a catalyst. As a result, carbon monoxide, hydrogen, and a tiny quantity of carbon dioxide is created. (U.S Department of Energy, 2016)

The vast majority of the hydrogen that is generated today originates from natural gas. The term "gray hydrogen" is used to refer to this kind of H<sub>2</sub>. Reforming natural gas with steam at high temperatures to create hydrogen from a methane source, such as natural gas, is referred to as NG steam-methane reforming. In the presence of a catalyst and at high pressure, the reaction between methane and steam results in the production of hydrogen, carbon monoxide, and a trace quantity of carbon dioxide. This procedure is endothermic, which means that the production of heat is necessary for the reaction to take place. Carbon monoxide and steam undergo a water-gas shift process in which a catalyst is involved. This reaction results in the production of carbon dioxide and more hydrogen. A stream of pure H<sub>2</sub> gas is produced as a consequence of the final stage, which is called pressure-swing absorption. This process involves removing CO<sub>2</sub> and other impurities from the gas. (Smoot, 2021).

### 3.2.2 Gasification

The process of converting coal or biomass into gaseous components is known as gasification. This procedure includes delivering heat under pressure to air/oxygen and steam, followed by the combustion of the resultant gaseous components. After a series of chemical reactions, syngas is created; this syngas is then reacted with steam to form a stream of hydrogen-rich gas. After its contact with steam, this gas stream may be isolated from the remainder of the mixture and cleaned. Using systems that capture and store carbon, it is possible to create hydrogen straight from coal with little emissions of greenhouse gases. Given that the growth of biomass results in the removal of carbon dioxide from the atmosphere, the synthesis of hydrogen from biomass by gasification results in near-zero net emissions of greenhouse gases in the absence of carbon capture and storage. (Alternative Fuels Data Center: Hydrogen Production and Distribution)



**Figure 20.** General process layout for Hydrogen production from gasification. (Hydrogen Production: Biomass Gasification, 2021)

Carbon monoxide, hydrogen, and carbon dioxide are the byproducts of gasification, which is a process that converts organic or fossil-based carbonaceous materials into carbon monoxide, hydrogen, and carbon dioxide at high temperatures (greater than 700 degrees Celsius) and without the use of combustion. The carbon monoxide will next undergo a water-gas shift reaction, which will result in the formation of carbon dioxide as well as more hydrogen. It is possible to remove the hydrogen from this gas stream using absorbers or specialized membranes. Simplified example reaction-  $C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2$

(Hydrogen Production: Biomass Gasification, 2021)

In a general sense, autothermal gasification can be carried out using either air, pure oxygen, or a combination of oxygen and steam. As a result, the heat required for the endothermic gasification processes is derived from the fuel's incomplete combustion. When air is used in the gasification process, the final product gas contains a significant amount of nitrogen that has been diluted. Because of the large percentage of nitrogen that makes up the resultant gas (about 45 to 55 percent), it has only a relatively modest calorific value (approximately 4 to 6 MJm<sup>-3</sup>), as seen above. In the process of allothermal gasification, the gasification agent can be either steam or CO<sub>2</sub> (or a mixture of the two). There are three distinct categories of technologies, and they are referred to as the Dual fluidized bed gasification technology, the MILENA gasification technology, and the heat pipe reformer technology. The following provides a concise explanation of them. (Rauch, 2018)

The key idea behind the dual fluidized bed (DFB) gasification concept is that the gasification process ought to be segmented into two separate zones. This is the core premise upon which the DFB gasification concept is founded. The combustion reactor, which is responsible for providing the heat necessary for endothermic gasification, is maintained separate from the gasification reactor, which is the location where oxygen-free gasification with steam takes

place. The gasification reactor is operated as a bubbling fluidized bed, and the steam that is used to fluidize the bed also serves the dual goal of acting as the agent that causes gasification. When it is operational, the combustion reactor functions as a fast fluidized bed, and air is utilized to power the reactor. Following the completion of the gasification step, the char and the bed material are transported to the combustion reactor. There, the char is given the opportunity to burn exothermically, which ultimately leads to the generation of heat. Because of this, the bed material is heated, and the circulation loop of bed material that connects these two reactors ensures that heat, which is necessary for the gasification process, is transferred from the combustion reactor to the gasification reactor. Wood gas and flue gas, both byproducts of combustion, are retained in their respective compartments thanks to the application of fluidized loop seals, which prevent the mixing of the two gases throughout the gasification process. As a consequence of this, the wood gas that is produced has a calorific value that is greater than 12 MJm<sup>-3</sup> and is almost completely devoid of nitrogen. Figure 21 depicts the usual constituents that are found in the product gas that is created by this sort of technology. (Rauch, 2018)

Components	Values	Units
H <sub>2</sub>	35-45%	m <sup>3</sup> ·m <sup>-3</sup>
CO	22-25%	m <sup>3</sup> ·m <sup>-3</sup>
CO <sub>2</sub>	20-25%	m <sup>3</sup> ·m <sup>-3</sup>
CH <sub>4</sub>	about 10%	m <sup>3</sup> ·m <sup>-3</sup>
C <sub>2</sub> H <sub>4</sub>	2-3%	m <sup>3</sup> ·m <sup>-3</sup>
Tar (incl. BTEX)	20-30	g·m <sup>-3</sup>

**Figure 21.** Typical gas composition of DFB gasification. (Rauch, 2018)

Both the DFB technology and the MILENA gasifier operate in accordance with a core principle that is astonishingly similar to one another in both appearance and operation. In addition to this, the MILENA gasifier is a method that works by combining the processes of two fluidized beds over the course of its operation. On the other hand, the gasification reactor

is run as a fast fluidized bed, while the combustion reactor is run as a bubbling fluidized bed. Both of these reactors are referred to collectively as the "combustion reactor" (BFB). The riser-like design of the reactor that is utilized allows for bed material and feedstock particles to be entrained together during the gasification process. This is made possible by the fact that the reactor is employed. Following their journey via the riser, the product particles are next removed from the product gas stream and transported to the zone of the bubbling fluidized bed reactor via the downcomer, which is also known as the settling section. This occurs after the product particles have been transported. In this system, as opposed to the DFB system, a smaller amount of steam is required as the gasifying medium; hence, the system as a whole achieves a higher cold gas efficiency (CGE). This is among the most significant benefits that come with using this approach. However, in the rapid fluidized bed gasification reactor, as opposed to the bubbling fluidized bed reactor that is used in the DFB system, the holding period for the product gas and the catalytically active bed material is significantly reduced. This is because the rapid fluidized bed gasification reactor has a higher fluidization rate. This is because the quick fluidized bed gasification reactor keeps the temperature at a higher level than normal while it is operating. Figure 22 depicts the typical components that are found in the product gas that is produced by utilizing this method. (Rauch, 2018)

Components	Values	Units
H <sub>2</sub>	27-28%	m <sup>3</sup> .m <sup>-3</sup>
CO	27-28%	m <sup>3</sup> .m <sup>-3</sup>
CO <sub>2</sub>	24-25%	m <sup>3</sup> .m <sup>-3</sup>
CH <sub>4</sub>	9-10%	m <sup>3</sup> .m <sup>-3</sup>
Tar (incl. BTEX)	18-20	g.m <sup>-3</sup>

**Figure 22.** Typical product gas composition from MILENA gasification. (Rauch, 2018)

The heat-pipe reformer is another method of allothermal gasification that may be utilized in the production of energy. The heat is transmitted from the stage of combustion to the stage of gasification via heat pipes in this approach, which is a considerable departure from the previous two methods that were covered before in this section. In addition, the gasification reactor, that is also known as the heat-pipe reformer when it is used in this configuration, is a pressurized vessel that is capable of functioning at temperatures as high as 800 degrees Celsius and pressures that range anywhere from 2-10 bar. The combustion reactor, which is positioned directly underneath the reactor that is used for the gasification process, provides the heat that is required for the gasification process. This heat is important for the gasification process. Both reactors are physically connected to one another through the use of heat pipes that run between them. Each of these heat pipes is loaded with a carrier medium as the heat is transferred from one pipe to another. This medium is then vaporized in the combustion reactor after it has been transported via the heat pipes. As a direct result of this process, the medium that has been evaporated carries the heat from the combustor to the gasifier. Once there, it condenses, releasing the heat that it had been holding onto. Both the combustion reactor and the gasification reactor are run as bubbling fluidized beds so that an acceptable amount of heat may be transferred from one process to the other. This is done in order to guarantee that both processes are able to function properly. The entrance point for the feedstock into the system is a standpipe, which is used when the feedstock is brought in. In addition to that, steam is poured in from the very top of the container. The usual composition of the gas that comprises the end product that is created by utilizing this approach is seen in Figure 23, which may be found below. (Rauch, 2018)

Components	Values	Units
H <sub>2</sub>	40-46%	m <sup>3</sup> ·m <sup>-3</sup>
CO	18-22%	m <sup>3</sup> ·m <sup>-3</sup>
CO <sub>2</sub>	20-26%	m <sup>3</sup> ·m <sup>-3</sup>
CH <sub>4</sub>	8-12%	m <sup>3</sup> ·m <sup>-3</sup>
Tar (excl. BTEX)	1-8	g·m <sup>-3</sup>

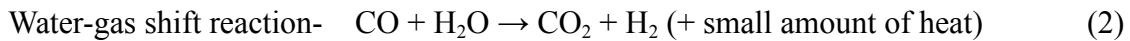
**Figure 23.** Typical product gas composition of heat pipe reformer gasification. (Rauch, 2018)

It can be seen that heat pipe reformer gasification produces the most amount of Hydrogen with the least amount of other harmful gases like CO and CO<sub>2</sub>.

### 3.2.3 Renewable Liquid Reforming

To generate hydrogen locally or remotely, biomass can be converted into high-mobility liquid fuels like ethanol and bio-oil, which can then be reacted with high-temperature steam. Vehicles may run on either of these fuels. Reformate gas is produced when liquid fuel and steam undergo high-temperature reactions in the presence of a catalyst. Carbon dioxide is found at extremely low concentrations in this gas mixture, which mostly consists of hydrogen and carbon monoxide. The "water-gas shift reaction" is the name given to this process, which results in the creation of both more hydrogen and carbon dioxide. The second step involves a reaction involving the interaction of the carbon monoxide produced in the first step with steam at a high temperature. Extraction of the hydrogen is followed by purification to complete the process. (Hydrogen Production: Biomass-Derived Liquid Reforming, 2021)

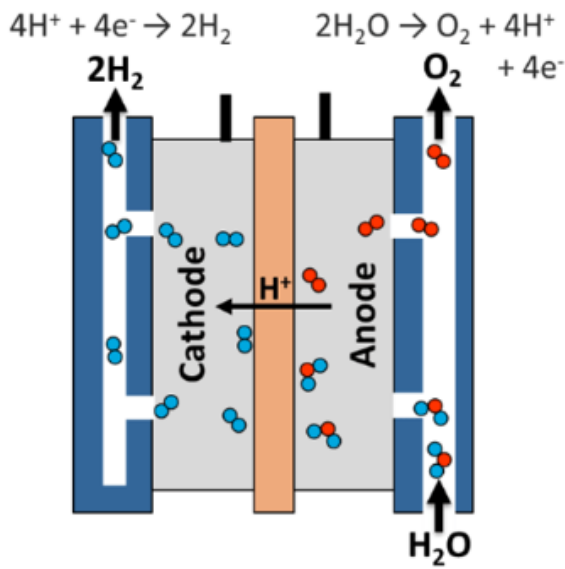




### 3.2.4 Electrolysis

Due to its reduced manufacturing costs, about 95 percent of hydrogen is created using hydrocarbons. The thermochemical method utilizes heat and chemical processes to liberate hydrogen from organic sources such as fossil fuels and biomass. Carbon emission is one of the disadvantages of this technique, especially in the absence of carbon capture. (Hydrogen Production Through Electrolysis, 2021)

Electrolysis is a process that utilizes an electric current to separate hydrogen from water. This process is known as electrolysis. The transformation of power into hydrogen gas is referred to as "power-to-gas" when it is carried out on a large commercial scale. In this context, "power" refers to energy, while "hydrogen" refers to gas. Electrolysis does not produce any byproducts or emissions of any type other than hydrogen and oxygen being the only two elements involved. The generation of electricity for electrolysis can come from a wide number of sources, such as renewable energy, nuclear energy, or fossil fuels. If the energy that is utilized for electrolysis is derived from fossil fuels (such as coal, natural gas, and petroleum), or from the burning of biomass, then the environmental effects and CO<sub>2</sub> emissions that are related with that hydrogen are indirectly associated with that hydrogen as well. When conducting high-temperature electrolysis to create hydrogen, it is feasible to improve the effectiveness of the electrolysis process by utilizing heat from industrial processes, such as nuclear reactors. This will allow for a more effective production of hydrogen. Since it takes less energy to split water into hydrogen and oxygen when the temperature of the water is greater, this means that raising the temperature of the water helps to minimize the overall amount of energy that is required. (U.S Department of Energy, 2016)



**Figure 24.** Simplified layout of water electrolysis system. (Hydrogen Production Through Electrolysis, 2021)

The electrolysis of water is accomplished by passing an electric current through water, which causes the water to separate into its basic components, hydrogen ( $\text{H}_2$ ) and oxygen ( $\text{O}_2$ ). This method generates hydrogen which may be utilized to store electrical energy as chemical energy. Due to the fact that the processing of water produces only oxygen as a byproduct, water is a great source for the synthesis of hydrogen. Green hydrogen is the name given to the hydrogen produced when a renewable energy source is employed in the process of separating water into hydrogen and oxygen. Electrolysis is the process of storing electrons in the form of stable chemical bonds, which transfers electrical energy into chemical energy. The freshly created chemical energy can be converted back into electrical energy or utilized as a fuel, depending on need. An electrolyzer, also known as an electrolysis cell, consists of two electrodes called the cathode and the anode, respectively. A cathode is an electrode with a negative charge, while an anode is an electrode with a positive charge. Both cathodes are surrounded by water and separated by an electrolyte membrane. There are several diverse types of electrolyzers, each of which accomplishes its principal job in a slightly unique manner owing to the employment of a particular type of electrolyte. Alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis are the most prevalent kinds of electrolysis done today. (Hydrogen Production Through Electrolysis, 2021)

Alkaline electrolysis, which makes use of potassium hydroxide, is the most established technique. It is widely utilized in the fertilizer and chlorine industries, despite the fact that it has significant limits. Alkaline electrolyzers (AE) account for the vast majority of large-scale electrolysis-based generation of hydrogen. They require 50 kWh per kilogram of hydrogen. PEM devices make use of sterile water and are relatively compact, and may be operated in a number of different ways. They are also capable of producing hydrogen at high pressure (30-60 bar, compared with alkaline 1-30 bar). However, they have a limited lifespan because of the costly electrode catalysts (platinum and iridium) and the membrane materials they require. They require 55 kWh for every kilogram of hydrogen. Electrolyzers based on solid oxides make use of ceramic materials and function at very high temperatures. They have very low starting speed and lower durability compared to other varieties. They require 40 kWh per kilogram of hydrogen. (Hydrogen Production and Uses, 2021)

### 3.2.5 Solar Thermochemical Water-Splitting

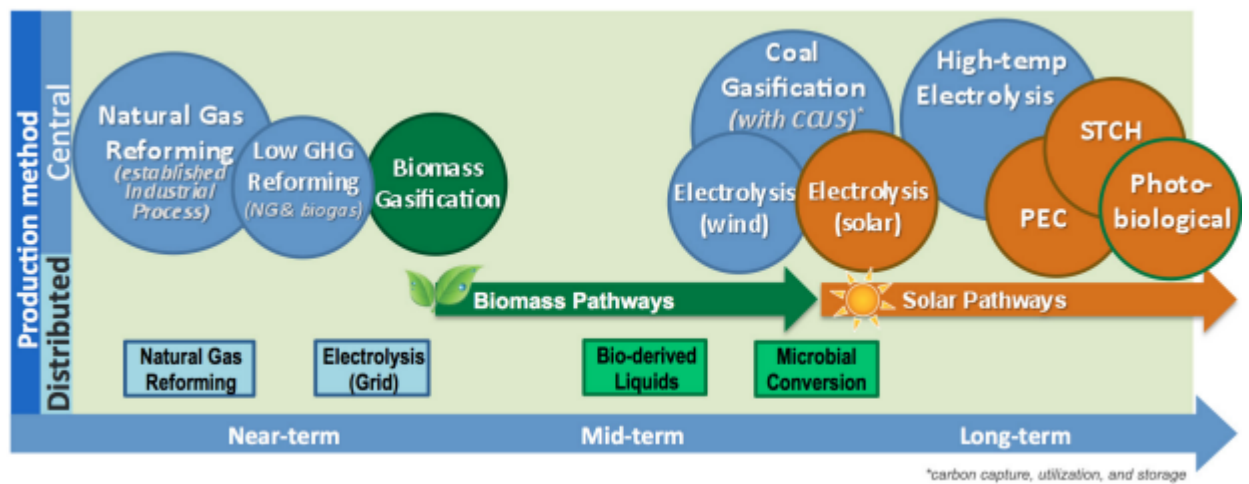
This method of water splitting makes use of the high temperatures produced by solar concentrators. It involves a series of reactions that are collectively referred to as solar thermochemical water-splitting cycles (TWSCs). These cycles are powered by the high temperatures produced by the sun. At the end of the process, hydrogen is produced, and oxygen is produced as a welcome by-product. Because the chemicals that are used are recycled, the final process is a closed-loop system that makes use of nothing but water as a feedstock and the heat from the sun to generate heat. A two-step process is the TWSC that is easiest to understand and implement. In the redox reactions involving metal oxides, a total of two endothermic reactions and one exothermic reaction are involved. The metal oxide is initially transformed into a reduced-valence metal oxide combined with oxygen, and then it is ultimately transformed into a reduced-valence metal oxide combined with hydrogen. Following this, the metal oxide with the lower valence reacts with water to produce hydrogen gas, oxygen, and the metal oxide that was first created. (Mastronardo, 2021)

### 3.2.6 Photoelectrochemical (PEC)

PEC water splitting is a method of producing hydrogen from water that makes use of sunlight and specialized semiconductors known as photoelectrochemical materials. These materials make use of light energy to directly separate water molecules into hydrogen and oxygen

atoms. PEC water splitting is an example of a method of producing hydrogen from water. This is a technology strategy that has been developed for the long term and has the potential to generate very few or even no greenhouse gases in the future. (Hydrogen Production: Photoelectrochemical Water Splitting, 2022)

As discussed in the above topic, these are some technologies which are being used or have potential to produce hydrogen with near zero emissions in future. But there are still some challenges that are faced while producing hydrogen. The main ongoing research revolves around these challenges and how to deal with them for better production of hydrogen. The most difficult task for hydrogen generation, particularly from renewable sources, is to provide hydrogen at a cheaper cost than is now available. Hydrogen must be cost-competitive with conventional fuels and technologies on a per-mile basis in order to be used in transportation fuel cells, which are a crucial driver of energy independence (U.S Department of Energy, 2016). In order to minimize the total cost of hydrogen, researchers are concentrating their efforts on enhancing the efficiency and longevity of hydrogen production technologies, as well as on lowering the costs of capital equipment, operations, and upkeep.



**Figure 25.** Examples of H<sub>2</sub> production processes. (U.S Department of Energy, 2016)

## 4. Carbon Footprint of Hydrogen Production

Hydrogen fuel is a clean-burning, zero-emission fuel that many feel has the potential to make a significant contribution to the fight against climate change. H<sub>2</sub> has one of the lowest potential carbon footprint of almost all the fuels available. When 3.78 liters of H<sub>2</sub> is combusted, it produces zero kilogram of CO<sub>2</sub> (Smoot, 2021). It helps to counteract climate change and provides a variety of environmental advantages. The process of H<sub>2</sub> creation, on the other hand, may nevertheless result in emissions. The "dirty secret" of hydrogen production is that it is mostly derived from fossil fuels. Consequently, whether hydrogen is truly "clean" is dependent on the technique of manufacture. Therefore, the carbon footprint of this process has to be taken into consideration while producing a massive amount of H<sub>2</sub> for future needs. (Forbes, 2020)

A Carbon Footprint is an objective method of measuring the impact that a piece of technology has had on the environment in terms of the emissions of greenhouse gases. This method was developed by the World Resources Institute (WRI) to measure the greenhouse gases and their potential effect caused on the environment by different technologies. (Carbon Footprint of the Hydrogen Production Process Utilizing Subbituminous Coal and Lignite Gasification, 2016)

### 4.1 Carbon Footprint using Steam methane reforming process

The steam methane reforming process is responsible for the production of more than 95% of the world's hydrogen. According to thermodynamics, when electricity is used to make hydrogen, the amount of energy produced will always be less than the amount of energy used. So as said, SMR is the main producer for H<sub>2</sub> globally. (Smoot, 2021)

First, as shown by the SMR and WGS reactions, one hundred percent of the carbon in the entering methane gets transformed to CO<sub>2</sub> at the end. Steam is responsible for the extra hydrogen that is created after the production of one molecule of carbon dioxide (CO<sub>2</sub>), which results in the production of four molecules of hydrogen (H<sub>2</sub>). Therefore, the production of 1 million standard cubic feet (SCF) of hydrogen from methane will result in the production of 250,000 SCF of carbon dioxide. Because one metric tonne of carbon dioxide contains 19,253 SCF, the conversion of one million SCF of hydrogen into carbon dioxide results in the

production of 13 metric tonnes of CO<sub>2</sub>. Thus, release of such a huge amount of CO<sub>2</sub> is the main drawback for SMR process (Forbes, 2020)

The second component is the individual carbon footprints left by each unit of the process. It is necessary to produce steam and to heat the reactor, among other things. However, steam is produced whenever the exhaust gas from the SMR is cooled, and this helps to counteract the carbon burden. The generation of one kilogramme (kg) of hydrogen through this process results in the production of 9.3 kilogrammes (kg) of carbon dioxide. One kilogramme of hydrogen has the same amount of energy as 3.78 liters of gasoline. Energy consumption is a common unit of measurement for carbon footprints. Kilowatt-hours (kWh) is the functional unit of measurement used when calculating the carbon footprint of power plants. There is 79,100 kWh of energy contained in one million standard cubic feet (SCF) of hydrogen. This equates to 0.28 kg of CO<sub>2</sub> being released into the atmosphere for every kWh that is spent producing hydrogen. (Forbes, 2020)

When H<sub>2</sub> is made from natural gas (NG), around 830 million tonnes of CO<sub>2</sub> are released into the atmosphere each year as a byproduct. This is the same amount of CO<sub>2</sub> emissions that are created when the United Kingdom and Indonesia are united. One of the major sources of hydrogen nowadays is steam reforming of natural gas, which also leads to the emission of 7.5 billion tons of carbon dioxide per year. The primary component of natural gas is known as methane (CH<sub>4</sub>), which is a gas that is capable of retaining heat over a period of one hundred years at a rate that is 34 times more efficient than that of CO<sub>2</sub>. (Smoot, 2021)

When we talk about the carbon footprint of specific sources of energy, such as coal, oil, and natural gas, we need to take into consideration carbon emissions during the construction phase, during operation, and during the decommissioning phase. NG has the lowest emissions of the three fossil fuels, coming in at 490 grams of CO<sub>2</sub> equivalent per kWh. This places it in third place among all of the other forms of fuel as well. After that comes coal, which emits an equivalent of 820 grams of CO<sub>2</sub> per kWh, and then comes oil, which emits an equivalent of 970 grams of CO<sub>2</sub> per kWh. In 2019, the global community collectively released 7.62 billion tons of CO<sub>2</sub> from NG, which was the least amount from any of the three fossil fuels (coal, oil, and NG). (Smoot, 2021)

## 4.2 Carbon Footprint using Electrolysis of Water

It is possible to calculate the unique carbon footprint associated with this generation of hydrogen by adding up the CO<sub>2</sub> emissions that are caused by the usage of byproducts in electrolyzers, the input materials, and the manufacturing process itself. The main source of carbon footprint in this process is caused by the electrolyzers which can be different according to usage. Electrolyzers may be broken down into three distinct categories: Alkaline Water (AE), Proton Exchange Membrane (PEM), and Solid Oxide Electrolyzer (SOE). (Hydrogen Production and Uses, 2021)

In order to reach similar findings for the overall energy demand of the water electrolysis technologies, it was required to account for not only the demand for electrical energy, but also the need for heat, as well as the subsequent compression of the hydrogen to a standard pressure of 30 bar. This was necessary for achieving comparable results for the overall energy consumption of water electrolysis methods. This was done so that there might be a better understanding of the entire quantity of energy necessary. The computations that are provided as part of the secret data given in figure 26 were performed in regions where access to accurate data was limited. (Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies, 2020). These calculations are shown in the image. Due to the fact that the solid oxide electrolyzer cell (SOEC) is still in the prototype stage and is not yet commercially viable, the total energy consumption of SOEC was measured by comparing data from the commercially accessible Sunfire SOEC to theoretical data acquired from public sources. This was done to determine the total amount of energy required by SOEC. This was done in order to accommodate the fact that the SOEC is still in the prototype phase. Even if the individual estimates for the electrical energy demand and the thermal energy demand were fairly varied, the total energy demands of all SOEC systems that have been considered fell within the same range as the energy requirements of the AEL and the PEM. This is the case despite the fact that the individual estimates for the electrical energy demand and the thermal energy demand were significantly different. This is because the total energy demand consists of multiple subsets, including the electrical energy demand and the thermal energy demand. Figure 26 depicts the outcomes of an analysis that included all information produced from data acquired in prior years. These data will be used to evaluate and contrast the carbon footprints created by the various electrolyzers by utilizing their

anticipated total energy consumption. (Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies, 2020)

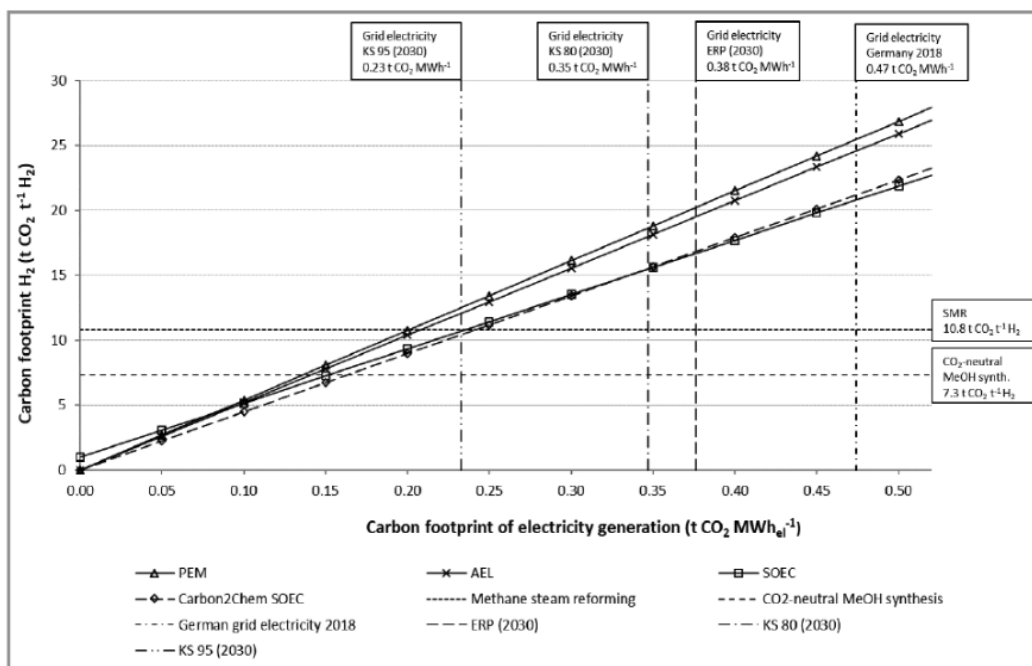
	AEL	PEM	SOEC I	SOEC II	SOEC III	SOEC IV	SOEC V	Integrated C2C-SOEC
Operating pressure [bar]	20 <sup>a)</sup>	30 <sup>a)</sup>	n.s.	5 <sup>a)</sup>	10 <sup>c)</sup>	n.s.	n.s.	10 <sup>c)</sup>
<i>Energy demand</i>								
Electrical energy [kWh Nm <sup>-3</sup> H <sub>2</sub> ]	4.64 <sup>a)</sup>	4.83 <sup>a)</sup>	3.70 <sup>a)</sup>	3.70 <sup>d)</sup>	3.70 <sup>f)</sup>	3.25 <sup>h,i)</sup>	2.95 <sup>j)</sup>	3.70 <sup>f)</sup>
Thermal energy demand [kWh Nm <sup>-3</sup> H <sub>2</sub> ]			n.s.	0.70 <sup>c)</sup>	0.70 <sup>c)</sup>	1.27 <sup>h,i)</sup>	1.37 <sup>j)</sup>	0.26 kWh <sub>el</sub> <sup>k)</sup>
H <sub>2</sub> compression to 30 bar [kWh Nm <sup>-3</sup> H <sub>2</sub> ]	0.02 <sup>b)</sup>			0.10 <sup>d)</sup>	0.06 <sup>g)</sup>	0.10 <sup>g)</sup>	0.10 <sup>g)</sup>	0.06 <sup>g)</sup>
Total energy demand [kWh Nm <sup>-3</sup> H <sub>2</sub> ]	4.66	4.83	4.70 <sup>d)</sup>	4.50	4.46	4.62	4.42	4.02

n.s. = not specified. a) Smolinka et al. [23]; b) calculated energy demand for compression of hydrogen from 20 to 30 bar; c) calculated thermal energy demand for steam generation (150 °C, 3 bar); d) calculated energy demand for compression of hydrogen from 5 to 30 bar; e) Schmidt et al. [16]; f) Sunfire-HyLink FactSheet [22]; g) calculated energy demand for compression of hydrogen from 10 to 30 bar; h) Mehmeti et al. [21]; i) Dai et al. [18]; j) Harvego et al. [20]; k) additional electricity demand as compensation for steam generation in power plant.

**Figure 26.** Assumption for total energy demand of different water electrolysis technologies. (Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies, 2020)

When a PEM is operated for 3000 h a<sup>-1</sup> using just electricity provided by renewables, the electrical energy source is still accountable for 96 percent of all greenhouse gas emissions, as stated in the study article that was prepared by Bareiß et al. The PEM stack is accountable for even less than one percent of the total greenhouse emissions, whereas the balance of plant, often known as BOP, is accountable for 4 percent of those emissions. As a consequence, the greatest possible contribution to the whole is less than 5 percent. In other situations, such as those with a larger load factor or a smaller proportion of the total power coming from renewables, the contributions of the BOP and the PEM stack is even less essential. This is due to load factors and proportions of total power are both higher in these situations. According to this, the availability of electrical energy is the primary contributor to the emissions of carbon dioxide that occur during the production of hydrogen that occurs during the electrolysis of water. These emissions take place throughout the process of producing hydrogen. The production of hydrogen results in the release of these pollutants at various stages during the process. Only the carbon dioxide emissions that come from the consumption of electrical

energy were taken into consideration since we wanted to keep things as straightforward and uncomplicated as possible. The carbon footprints of AEL, PEM, and SOEC were evaluated in order to see how they stacked up against SMR. These carbon footprints were estimated as a function of the carbon footprint of the electrical generation. The projection for the entire amount of energy consumption was utilized as the starting point for the calculations, and the results can be seen in Figure 27. (Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies, 2020)



**Figure 27.** Carbon footprint of hydrogen production via water electrolysis as a function of the carbon footprint of electricity used (Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies, 2020)

In addition to the growth of renewable energy sources, continued technological advancements in water electrolysis will also contribute to the reduction of the global carbon footprint. Because of the decreased need for specified amounts of electrical energy, the AEL and the SOEC will have a smaller carbon footprint by the year 2030 as a result of the generation of hydrogen. In the case of the PEM, the specific energy demand will also be slightly reduced in the coming years; however, the priority will be placed on lowering the CAPEX in order to compensate for the economic benefits of the AEL, rather than improving the efficiency of the

system. (Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies, 2020)

#### 4.3 Carbon Footprint using Coal and Lignite Gasification

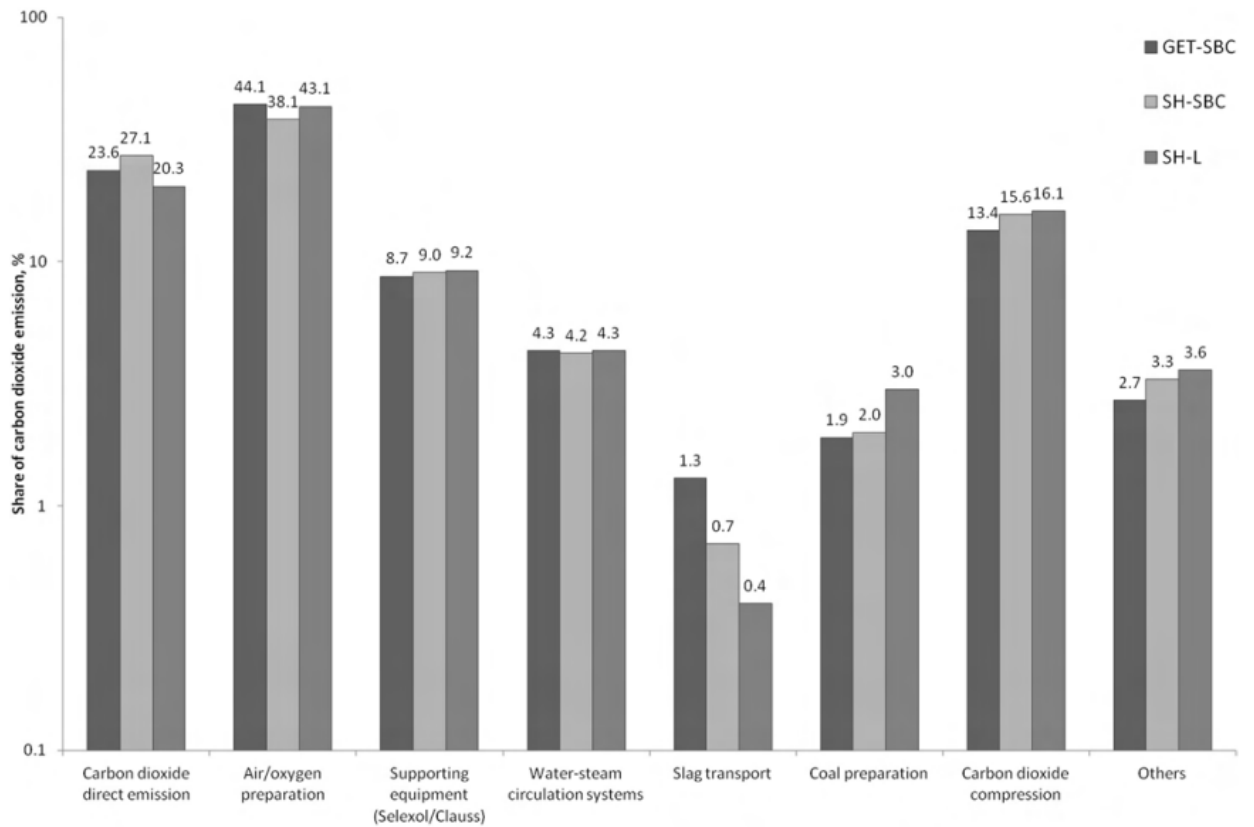
With a great advantage of their low cost and widespread availability, subbituminous coal and lignite are the two fuels that are most commonly used in the gasification process. In one of the scientific study publications, the carbon footprint was calculated by making use of two different fuels, namely lignite (L) and sub bituminous coal (SBC), in addition to two different gasification processes, namely GE Energy/Texaco (GET), and Shell. This was done in order to account for all of the variables that could potentially influence the results (SH). The CO<sub>2</sub> emission that was produced as a direct result of the hydrogen generating cycle was the subject of several calculations and evaluations. This study investigated not only the mining of coal but also the chemical processing of coal, the transportation of coal to the gasification plant, the process of gasification itself, and the sequestration of CO<sub>2</sub> that was captured. The following is a summary of the findings that were derived from the values that were provided in the article. These conclusions were reached after doing the research.(Carbon Footprint of the Hydrogen Production Process Utilizing Subbituminous Coal and Lignite Gasification, 2016)

Emission indicators	kg CO <sub>2</sub> GJ <sup>-1</sup> of coal			kg CO <sub>2</sub> (kg H <sub>2</sub> ) <sup>-1</sup>	
	GET, SBC	SH, SBC	SH, L	GET, SBC	SH, SBC
Hydrogen production technology					
Coal production	1.94	1.94	3.24	0.416	0.383
Transport of coal	0.19	0.19	0.35	0.041	0.038
Purchase of energy, net	8.41	4.17	11.53	1.799	0.821
Purchase of electricity, net	8.41	4.17	11.53	1.799	0.821
Purchase of heat, net	0	0	0	0	0
CO <sub>2</sub> direct emissions	7.37	8.27	8.66	1.577	1.630
CO <sub>2</sub> captured (sequestration)	83.49	83.99	93.48	17.870	16.552
Energy consumption on sequestration	6.41	6.45	9.35	1.373	1.271
<b>Total emissions without sequestration</b>	<b>101.40</b>	<b>98.56</b>	<b>117.26</b>	<b>21.703</b>	<b>19.424</b>
<b>Total emissions with sequestration</b>	<b>24.32</b>	<b>21.02</b>	<b>33.13</b>	<b>5.206</b>	<b>4.143</b>

**Figure 28.** Emissions of hydrogen production by gasification. (Carbon Footprint of the Hydrogen Production Process Utilizing Subbituminous Coal and Lignite Gasification, 2016)

The CF value for the SH method of SBC gasification was the lowest of any step in the hydrogen generation cycle. This was because the SH method generated more hydrogen than CO<sub>2</sub> throughout the reaction. The CF value of 19.4 kg CO<sub>2</sub> kg<sup>-1</sup> H<sub>2</sub> was calculated because

CO<sub>2</sub> was removed during the production of hydrogen using this technique, but the gas was not sequestered. To this extent, it was possible to get. L's SH technology used 25.3 kg of carbon dioxide to produce 1 kg of hydrogen, whereas SBC's GET technology required 21.7 kg of carbon dioxide to produce 1 kg of hydrogen. This means that L's SH technology emits more carbon dioxide than SBC's GET technology does per kilogram of hydrogen. Coal extraction was responsible for between 1.9 and 2.8 percent of pollutants in SBC and L, respectively. A wide range of coal production-related pollution's overall contribution to total emissions was discovered. Emissions produced during transit were minimal, with values ranging from 0.2% for SBC to 0.3% for L (with L having the highest value). The majority of the CF (97.0% for L and 97.8% for SBC, respectively) was produced by the gasification process, which incorporates all of the ancillary processes. Approximately 79%-84% of all emissions were direct CO<sub>2</sub> emissions, which were released during the gasification process. Furthermore, carbon sequestration is a technique that may be used within this process, and it is a choice that we may choose. Hydrogen is a "low-carbon" fuel that may be obtained at a cost that is comparable with the carbon-heavy generation of electricity. With this technology, hydrogen might be extracted in a way that is both realistic and practical. Hydrogen might be obtained in this way if the production process were combined with the sequestration process. By putting the captured CO<sub>2</sub> to use in the gasification process and in ancillary processes, the CF underwent structural changes caused by the sequestration of the CO<sub>2</sub>. The CO<sub>2</sub> collection led to these alterations (Figure 28). Direct emissions from the gasification process accounted for 20-27% of the total CF produced, which is a considerable reduction from the 79-84% produced by the non-sequestration type. However, CF had to be included because it was produced during the CO<sub>2</sub> compression storage process. As of a few years ago, it owned around 15% of the business. The gasification process's CF was most heavily influenced by the pretreatment of air and oxygen. It was the most crucial supporting operation, thus it got special attention. Next came water-steam cycles (about 4 percent) and preparing coal for gasification (around 9 percent), while gas desulfurization and sulfur recovery accounted for around 9 percent (which accounted for approximately 4 percent). (Carbon Footprint of the Hydrogen Production Process Utilizing Subbituminous Coal and Lignite Gasification, 2016)



**Figure 29.** CO<sub>2</sub> emissions at various stages of the gasification process with CO<sub>2</sub> sequestration. (Carbon Footprint of the Hydrogen Production Process Utilizing Subbituminous Coal and Lignite Gasification, 2016)

We can see the summary of the carbon footprint of different hydrogen production technologies in Figure 30. This figure will be also considered to answer some of the questions in chapter 5.

Technology	CO <sub>2</sub> footprint kg CO <sub>2</sub> e kg <sup>-1</sup> H <sub>2</sub>
Steam methane reforming	10.1–17.2 <sup>b</sup>
Coal gasification	14.7–26.1 <sup>b</sup>
CH <sub>4</sub> pyrolysis	4.2–9.1 <sup>b</sup>
Biomass	0.3–8.6 <sup>b</sup>
Electrolysis, electricity supply from natural gas combined cycle turbine <sup>a</sup>	23.0 <sup>b</sup>
Electrolysis, wind electricity <sup>a</sup>	0.5–1.1 <sup>b</sup>
Electrolysis, solar electricity <sup>a</sup>	1.3–2.5 <sup>b</sup>
Electrolysis, nuclear electricity <sup>a</sup>	0.5–1.0 <sup>b</sup>

<sup>a</sup> Specific energy consumption of water electrolysis: 51.2 kWh kg<sup>-1</sup> H<sub>2</sub>; average life-cycle CO<sub>2</sub> emissions: 467 kg CO<sub>2</sub> MWh<sup>-1</sup> (electricity supply from natural gas combined cycle turbine), 9.4–21.4 kg CO<sub>2</sub> MWh<sup>-1</sup> (wind electricity), 25.0–48.0 kg CO<sub>2</sub> MWh<sup>-1</sup> (solar electricity), 8.4–18.0 kg CO<sub>2</sub> MWh<sup>-1</sup> (nuclear electricity);

<sup>b</sup> Parkinson et al. <sup>6</sup>.

**Figure 30.** Summary of CO<sub>2</sub> produced from different hydrogen production technologies. (Smoot, 2022)

## 5. Discussion

Before I put the finishing touches on my master's thesis, I believe it is important to share some of my own insights and ideas on the prospective uses of hydrogen in the years to come. Since the generation of hydrogen is currently one of the sources of greenhouse gas emissions throughout the world, there should in the first place be an effort made to generate hydrogen with a low carbon footprint. At current time, the production of hydrogen to meet the demand resulted in the emission of around 830 million tons of carbon dioxide. It is responsible for around 2.3% of the world's total yearly CO<sub>2</sub> emissions. Whereas back in 2019, it was predicted to be around 440 millions of tons. As a consequence of this, the production of hydrogen is currently a contributor to pollution on a global scale. As a consequence of this, there is a significant motivation to decarbonize this industry, and this is unquestionably the primary and most essential goal of the development of green hydrogen. (Louvet, 2021)

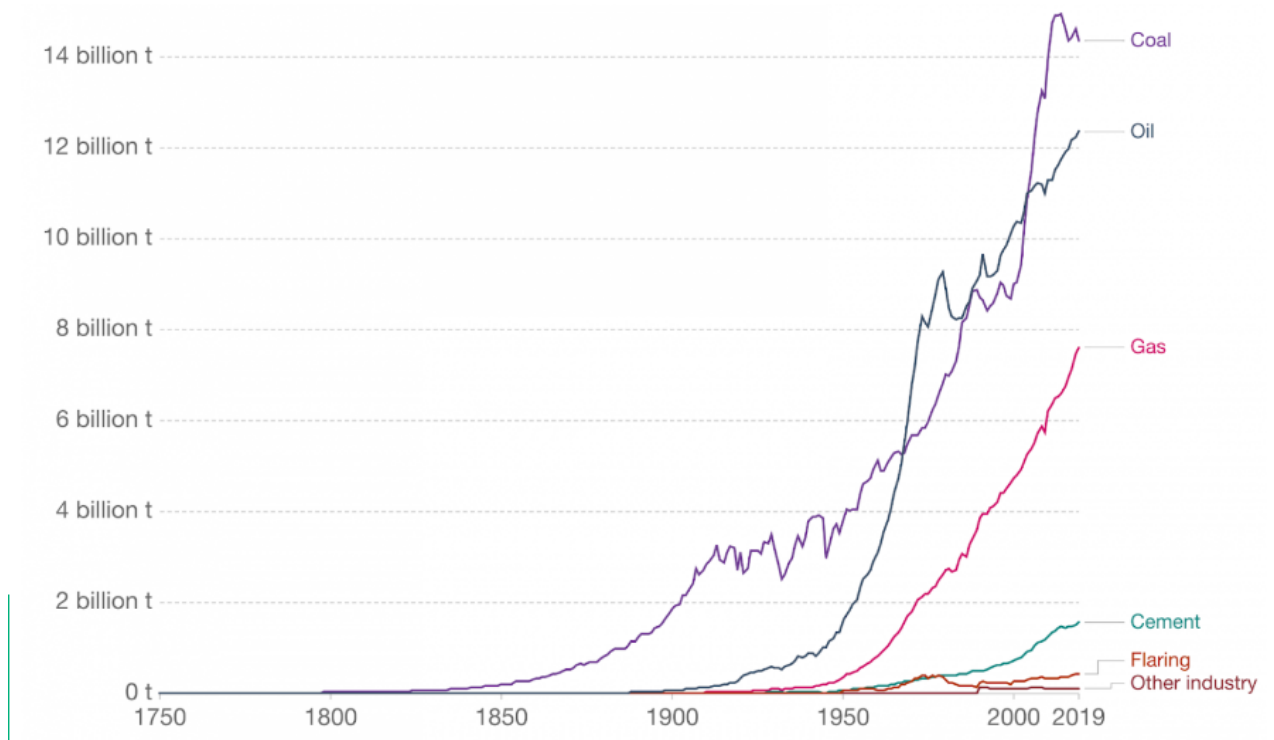
### 5.1 Why is green hydrogen a better fuel than conventional fossil fuels in transportation

Fossil fuels are one of the most used fuels in the transportation sector for centuries. They are widely used in different sectors of mobility such as road transport, railways, aviation and ships. They are reliable sources of energy with great efficiency and power to serve the purpose of traveling. But due to the excess use of these fuels from the past centuries, there has been a subsequent increase in global temperature resulting in global warming across the globe. The GHG emissions done by these fuels trap the heat and promote global warming which is one of the major concerns regarding the future of the globe. There are emissions when using these fuels as a source of energy as well as while extracting them from the ground. Further under this topic we will compare the carbon footprint of conventional fossil fuels over hydrogen. This will help us to acknowledge the fact that hydrogen is a better fuel with regard to conventional fuel.

The carbon footprints left by fossil fuels are among the largest of all types of energy sources. On a life-cycle basis, the production of one kWh using oil results in 970 grams of carbon dioxide emissions, while the production of one kWh using coal results in 820 grams of emissions. They are regarded as dirty energy since they contribute directly to climate change, have a variety of adverse consequences on the environment, and cause other problems. Since

the beginning of the industrial revolution, fossil fuels have been the primary source of electricity for our homes, automobiles, and other forms of transportation. They are made up of fossil fuels like coal, oil, and natural gas (NG), all of which were produced over the course of millions of years in the past. The emission rate of oil is the highest among all forms of fuels, coming in at 970 grams of CO<sub>2</sub> equivalent per kilowatt hour (gCO<sub>2</sub>/KWh). (Smoot, 2022)

In 2019, global CO<sub>2</sub> emissions from coal were 14.36 billion tons, those from oil were 12.36 billion tons, and those from natural gas were 7.62 billion tons. (Smoot, 2022)



**Figure 31.** CO<sub>2</sub> emissions by fuel, World. (Smoot, 2022)

The two major fuels for transportation are derived from crude oil which are gasoline and diesel. Let's see the breakdown of these fuels in regard to the carbon footprint produced by them. The combustion of 3.78 liters of gasoline results in the release of about 9.07 kilograms of carbon dioxide into the atmosphere. Hydrogen and carbon are produced by the combustion of gasoline. After that, the hydrogen mixes with the oxygen to become water, often known as H<sub>2</sub>O, and the carbon interacts with the oxygen in the air to make carbon dioxide, CO<sub>2</sub>. The burning of gasoline is particularly damaging to the environment because, for every pound of gasoline that is burnt, more than three times that amount is emitted as CO<sub>2</sub>; this makes

gasoline combustion one of the most environmentally damaging human activities. In 2019, the consumption of oil exceeded 53,000 terawatt-hours, making it the most energy-intensive of the three primary fossil fuels. Burning fossil fuels has many negative effects on the environment, but one of the most serious is undoubtedly climate change. When fossil fuels are used, they release around 36 bt of CO<sub>2</sub> into the atmosphere each year. Oil contributes 12 bt, or 34%, to this total. The carbon that is present in gasoline has a chemical reaction with the oxygen that is present in the air to form carbon dioxide, which works as a heating blanket to warm the earth. (Smoot, 2022)

Burning of Gasoline	Carbon footprint
Burning one gallon	<u>8,887</u> grams of CO <sub>2</sub> emitted
Driving one mile (on average)	<u>404</u> grams of CO <sub>2</sub> emitted
Per million British thermal units (Btu)	<u>155.77</u> pounds of CO <sub>2</sub> emitted

**Figure 32.** Carbon footprint of gasoline. (Smoot, 2022)

The majority of the world's transportation fuel comes from oil in the form of diesel. "Light-middle" and "middle" diesel distillates are used in vehicles and trucks with high-speed engines, whereas "heavy" distillates are used in trains, ships, and stationary engines with low and medium-speed engines. Low-grade diesel, which produces the least amount of volatile byproducts, is utilized in low-speed engines as opposed to high-grade diesel, which is utilized in high-speed engines. The amount of carbon residue left behind by low-grade diesel is often higher, and it also has a higher concentration of sulfur. The combustion of 3.78 liters of diesel results in the production of around 10.15 kilograms of carbon dioxide, despite the fact that the 3.78 liters only weighs about 3.17 kilograms. Hydrogen and carbon are produced by the combustion of diesel. After that, the hydrogen mixes with the oxygen to become water, often known as H<sub>2</sub>O, and the carbon interacts with the oxygen in the air to make carbon dioxide, CO<sub>2</sub>. The chemical formula for diesel consists of 12 atoms of carbon and 23 atoms of hydrogen. When compared to gasoline, which only has eight carbon and eighteen hydrogen atoms, diesel fuel has twenty more carbon atoms, which means that diesel's combustion results in greater emissions of greenhouse gases. When diesel fuel is burnt, more than three times as much carbon dioxide as was originally contained in the diesel is released into the

atmosphere as a byproduct. This makes diesel combustion one of the most environmentally destructive processes. (Smoot, 2022)

Burning of diesel fuel	Carbon footprint
Burning one gallon	<u>10,180</u> grams CO <sub>2</sub> / gallon
Driving one mile (on average)	<u>404</u> grams of CO <sub>2</sub> emitted
Per million British thermal units (Btu)	<u>163.36</u> pounds of CO <sub>2</sub> emitted

**Figure 33.** Carbon footprint of Diesel. (Smoot, 2022)

As discussed above, we can clearly see how much emissions fossil fuels have which are really harmful on a mass scale. On the other hand, using green hydrogen as a fuel has zero emissions. But still there are some emissions while producing hydrogen. Although, they are less than that of conventional fuel but as the demand increases it can also increase. Therefore, to make hydrogen a real game changer in the transportation sector newer technologies should come into play to produce the hydrogen with the least carbon footprint. These technologies should be mainly derived from renewable sources. As discussed in Chapter 4, we can see how much carbon footprint there is while producing hydrogen from different technologies. (Figure 30)

Even when taking into consideration the production of H<sub>2</sub> from NG as well as its distribution and storage for use in FCEVs, it is possible for H<sub>2</sub> to reduce greenhouse gas emissions by fifty percent and cut use of petroleum by ninety percent. This reduction in GHG emissions, in turn, lessens the consequences of global climate change, including increases in temperature, rises in sea levels, melting of sea ice, changes in precipitation patterns, and acidification of the ocean. In order to calculate the carbon footprint of transporting H<sub>2</sub> fuel, one must first determine where the H<sub>2</sub> fuel is created, then determine where it is consumed, and then determine the distance between the two locations. There are now just a handful of nations that can generate H<sub>2</sub> fuel and transport it, but only a few of those countries also produce it. (Smoot, 2022)

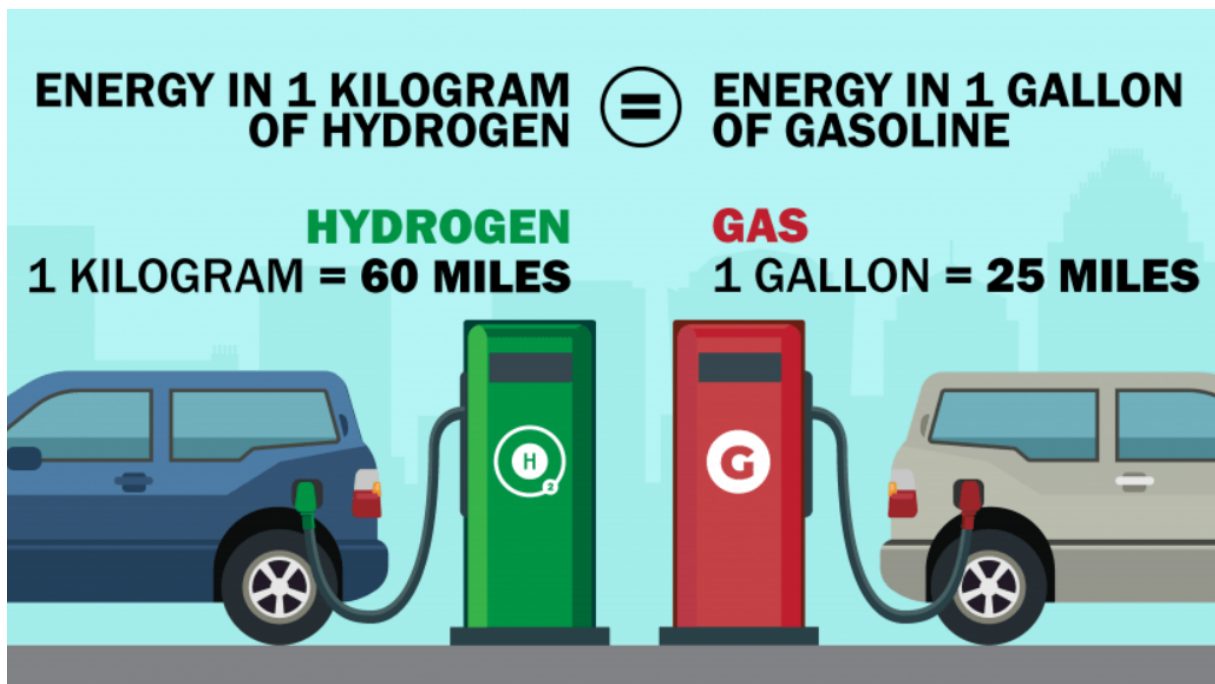
Hydrogen energy has a number of commendable benefits, but it is not the most preferred, pure, and affordable energy source among many organizations. In its gaseous form, it is extremely volatile. There are numerous disadvantages, such as hydrogen energy is expensive. The two primary methods of hydrogen extraction, electrolysis and steam reforming, are exceedingly expensive. This is the true reason why it is not widely used throughout the globe. Secondly, it has storage difficulties. One of the properties of hydrogen is that it has a reduced density. It is significantly less dense than petroleum. To guarantee its efficacy and efficiency as an energy source, it must be compressed into a liquid state and stored in the same manner at reduced temperatures. This also explains why hydrogen must always be stored and transported under high pressure, making transportation and widespread use impractical. Also, it is not the safest energy source. Hydrogen's adverse effects should not be underestimated in any way. Although petroleum is slightly more hazardous than hydrogen, hydrogen is a highly flammable and volatile substance whose potential hazards frequently make headlines. Hydrogen lacks odor compared to gas, making breach detection nearly impossible. To detect leakage, sensors must be installed. (Advantages & Disadvantages of Hydrogen Energy, 2021)

## 5.2 Is it possible to convert the whole transportation sector to hydrogen driven

Theoretically, hydrogen has the capability of decarbonizing everything from the steel that was used to create someone's automobile to the gas that is used to heat their home. In actuality, though, it is quite improbable that hydrogen will be used everywhere. Even if production were significantly scaled up, it is highly likely that the volume required to satisfy all of the possible applications for low-carbon hydrogen would far exceed the amount that is currently available. Moreover, the volume required to satisfy all of these applications would likely be significantly higher. The mobility sector now accounts for less than 0.1% of the total demand in the hydrogen market, making it the industry's least important component. Hydrogen's potential to flourish in the transportation business has garnered support from a wide variety of market participants, and the substance is now being utilized in a few specialized industries. As an illustration, there are around 25,000 forklifts that are now powered by hydrogen. There is a possibility that hydrogen may continue to play an important part in transportation modes that are more difficult to decarbonize, such as long-distance trucks and airplanes; however, the development of many of these fields is still in its infancy. Both the aviation industry and

the shipping industry are notoriously difficult to electrify. Together, they are responsible for around 5% of world emissions. Therefore, hydrogen or fuels based on hydrogen, such as ammonia, could be absolutely necessary in order to achieve net-zero objectives. There is a fear that hydrogen might eat cargo storage and, as a result, revenues since hydrogen requires at least five times more room than oil-based fuels in order to be stored. One of the solutions to the previous statements can be optimized by using liquid hydrogen as the source of energy. The railroad is the last possible form of transportation that may profit from hydrogen. With three-quarters of passenger transportation taking place on electric trains, rail is already the form of transportation that has the highest percentage of electrification worldwide. (Goodman, 2020)

There are still a variety of factors to consider, which makes it extremely challenging to transform the whole transportation industry into one that is powered by hydrogen. The fact that it is a relatively new technology means that it is prohibitively expensive for the average person to purchase; this is the primary drawback. Additionally, there is not enough infrastructure to facilitate the widespread use of this technology. Second, it is not very environmentally friendly because nearly all of the hydrogen is still generated from fossil fuels. But if we want to move around in a way that is genuinely sustainable, we can't dismiss hydrogen as a fuel. It is also considered a viable option for powering heavy-duty vehicles (HGVs), which has challenges in the form of limited battery capacity as well as the requirement to recharge using the power grid. The most significant drawback, on the other hand, is that establishing a complete infrastructure for hydrogen refueling, in which the gas is first generated and then transported to stations, will take a number of years and billions of kilograms to accomplish. Hydrogen has several advantages, one of which is that it may be created locally rather than being transported like gasoline or delivered through the grid like electricity. (Wilkinson, 2022)



**Figure 34.** Energy of hydrogen compared to gasoline. (Wilkinson, 2022)

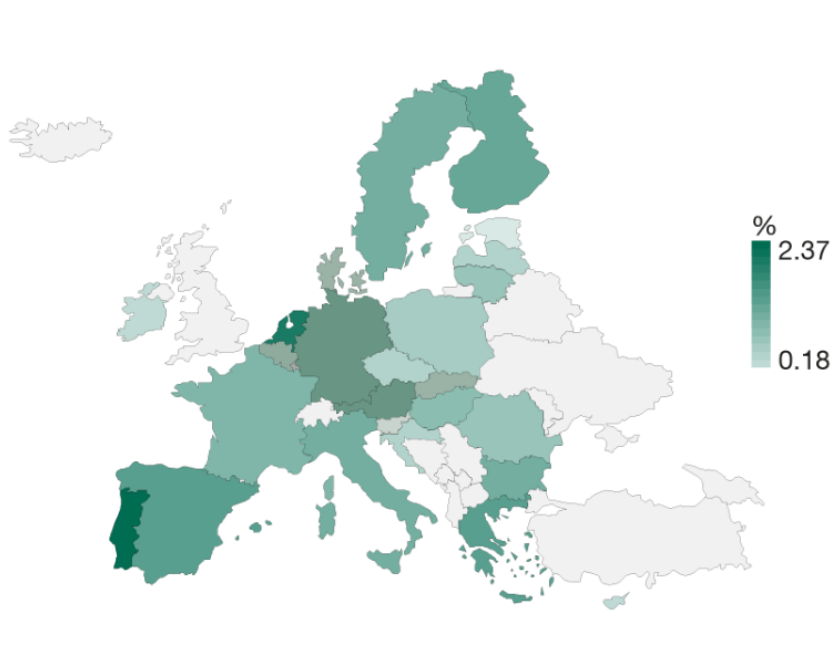
### 5.3 Predictions on future hydrogen production and transport sector in Europe

Hydrogen plan for a climate-neutral Europe was the title of a paper that was published in July by the European Commission (2020). It takes the shape of a blueprint that clearly defines the actions that must be implemented in order to create and expand value chains that are dependent on the production of "green" hydrogen. According to the definition of "green" that was decided upon by the EU, hydrogen may be considered "green" if it is produced through the process of water electrolysis and the electrical power that is used as a source comes from sources that are continually replenished or are environmentally friendly. In other words, hydrogen may be considered "green" if it is produced in a manner that is environmentally friendly. The road plan outlines a route that will develop across the course of three separate stages. During this phase, which will continue through 2024, the production of hydrogen that is safe for the environment and can be used in applications that have already been created will be the primary focus of attention. The majority of these are restricted to the chemical industry, which is the only industry that makes a significant use of hydrogen as a feedstock in the production of fertilizers at the current moment. At the same time, we ought to be encouraging customers to use new applications by providing gentle nudges in that direction. In order to accomplish this goal, the construction of electrolyzers with a combined

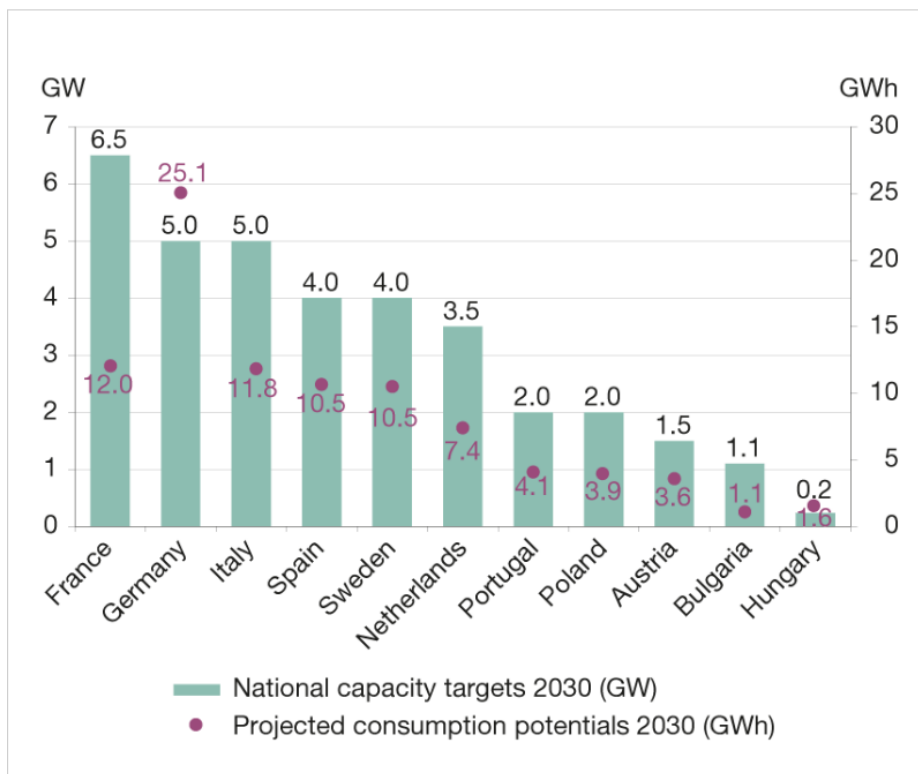
capacity of six gigawatts (GW) is now under way. These electrolyzers have the capability of producing up to one million tons of hydrogen per year that is not harmful to the surrounding environment. It is anticipated that the use of electrolyzers will pick up pace between the years 2025 and 2030, and it is likely that hydrogen will conquer new application industries during this time period. This prediction is based on the fact that the implementation of electrolyzers is anticipated to speed up. These new application areas include the function of power sources in energy-intensive industries (like steel), as well as diverse uses in the transportation sector. Other applications include the function of power sources in the medical sector. The use of energy carriers in the field of medicine is another example of a novel use of this technology. It is anticipated that the overall capacity of electrolyzers would reach 40 GW by the year 2030, which corresponds to an annual generation of around 10 million tons of hydrogen. This estimate was based on the existing state of affairs. This is because it is expected that electrolyzer capacity would increase. Last but not least, beginning in 2030 and continuing into the future, the use of environmentally friendly hydrogen will expand to all application areas where it is technically viable and has economic advantages over other environmentally friendly technologies. (Wolf & Zander, 2021)

The EU Reference Scenario 2020, which is the European Commission's (2020) energy perspective and is based on the regulatory framework, provides the most complete comparative assessment of the future growth of power consumption at the national level. As a direct result, considerable cultural differences between nations are the driving force behind changes in consumption trends. Seven of the 27 EU member nations, including France and Germany, are anticipated to have reduced their overall energy use by 2030, compared to the base year of 2020. This is the case when comparing the 2030 scenario to the 2020 situation. In contrast, the data indicates that a number of significant nations in Central and Eastern Europe, such as Hungary, Poland, Bulgaria, and Romania, may experience very strong increases, with consumption levels anticipated to increase by more than 10% by 2030. By 2030, this increase is anticipated in a few of these nations. (Union of European Commission, 2021a). In contrast, many governments are not as active as others in pursuing their ambitions for the growth of renewable energy sources. To accurately examine the potential role that hydrogen will play in the future of nations, it is essential to do in-depth research on both policy objectives and demand-based demands. Then only can an appropriate evaluation of that job be formed. Recent research commissioned by the European public-private partnership Fuel Cells and

Hydrogen Joint Undertaking generated demand and production predictions for environmentally friendly hydrogen in EU member states. These scenarios were constructed utilizing the infrastructure, economic structure, and policy environment of the individual countries as their major data sources. Due to Germany's vast market potential, it is anticipated that the nation would have the biggest production capacity by a considerable margin. According to a scenario average, Germany's predicted capacity (8.35 GW) is more than double that of France, the world's second-largest producer at now (3.25 GW). It is anticipated that Spain, with a capacity of 2.55 GW, and the Netherlands, with a capacity of 2.2 GW, will both become significant producers in absolute terms (Trinomics and LBST, 2020). To estimate the future relevance of hydrogen on a national scale, however, it is necessary to examine the predicted expansion trajectories in relation to the rise of overall energy consumption. The future relevance of hydrogen can only then be established. Consequently, a more accurate evaluation will be possible. From this perspective, the pattern has a whole different appearance. Figure 35 is a mapping that illustrates the relationship between Trinomics and LBST's (2020) projections for the national consumption of hydrogen and the EU's projections for the total consumption of energy. The forecasts were developed for the year 2020. The whole range of hydrogen coverage is between one percent and two percent. This range spans the whole hydrogen coverage spectrum. In spite of the fact that coverage rates in Austria, Finland, Germany, Greece, the Netherlands, and Spain are above average, the greatest rate is found in Portugal, where it is anticipated that hydrogen would supply 2.37 percent of total final energy demand in 2030. This rate is far higher than that of any other country on the earth. (Wolf & Zander, 2021)



**Figure 35.** Potential future hydrogen coverage in the EU Trinomics and LBST combined. (Wolf & Zander, 2021)



**Figure 36.** Green hydrogen capacity and consumption potentials in the EU. (Wolf & Zander, 2021)

Plans being considered by member states as appropriate in this regard lack the amount of information that would be necessary in such a circumstance, as was just said. Within the European Union, eleven of the twenty-seven member states have set goals to increase electrolyzer capacity. There isn't usually a direct correlation between such possibilities and real customer usage among them (Figure 36). Despite having a predicted consumption potential that is more than twice as high as France's, Germany has set a capacity objective for itself that is lower than France's. In spite of having nearly the same potential as France, current policy aims in Spain are far less aggressive. Hungarian plans for future enrolment of electrolysers are among the most modest that have been recorded, despite the country's usage potential being within the range of countries with comparable economic proportions. Because Hungary has the least ambitious plans to build electrolysers, it will produce the least quantity of hydrogen per capita. While just the most basic of Hungary's goals have been made public, the current situation is still this. Countries like Italy, Sweden, and the Netherlands that have the potential to be major consumers have plans that are more in line with consumption forecasts. (Wolf & Zander, 2021)

The European Union's stricter climate standards have given the research and development of ecologically friendly technologies of producing hydrogen a larger importance in national efforts to accomplish the energy transition. Currently, nearly all EU member states have published or are working to adopt hydrogen plans. While all plans have an element of guesswork, the degree to which that guesswork is accurate and the scope to which it extends vary widely. In terms of aggregated consumption, several distinct clusters of countries may be defined with high precision. For instance, decarbonizing Mediterranean countries may be greatly aided by green hydrogen. However, in Eastern Europe, where emissions restrictions are not as rigorous as elsewhere, hydrogen has the potential to make a significant relative contribution. If the hydrogen economy is to be successfully implemented, planning must go beyond just competing to increase electrolysis capacities. The EU's structural imbalances in production and consumption give an opportunity for a new European division of labor inside a common hydrogen network. This is a chance to demonstrate the importance of multilateral collaboration in the design of a European hydrogen infrastructure. (A Hydrogen Strategy for a Climate-Neutral Europe, 2020)

## 6. Conclusion

Certain research concerns that guided the development of the thesis are addressed in this chapter. Questions included, "What is Green Hydrogen? ", "What is its production and carbon impact during manufacturing? ", and "Can it be utilized in the near future to change the European transportation industry into a carbon neutral transportation sector?"

Whenever people talk regarding hydrogen, they are often referring to hydrogen gas, which is a colorless, odorless, and clear gas that has a relatively low density and may be used as a fuel. Hydrogen may play a significant role in the energy transition not as a new main energy source but rather as an energy carrier that is able to convey renewable energy deeper into the market. This would mean that hydrogen would not be a new primary energy source but rather an energy carrier. Paying great attention to the source of the hydrogen being produced is necessary in order to find a method of producing hydrogen with a carbon footprint that is as little as possible. The steam methane reforming process is the most common technique of producing hydrogen, which is used for the vast majority of the world's current applications of hydrogen, which are produced from fossil fuels (SMR). Because of this, it is responsible for the release of 10 to 20 kg of CO<sub>2</sub> for each kilogram of hydrogen that is produced. Gray hydrogen is a frequent name for this kind of hydrogen, which contains a lot of carbon. The creation of hydrogen without the SMR process would lead to a significant reduction in the amount of carbon emissions. The form of the hydrogen molecule is referred to as "green hydrogen" when it is created from energy sources that are both clean and renewable. On the other hand, blue hydrogen is produced with little carbon emissions but does not directly employ renewables; rather, it is produced through the use of carbon capture and storage or through the usage of nuclear energy.

To produce green hydrogen, the electrolysis of water using electricity derived from renewable sources is the most developed of the various techniques that may be used to create hydrogen from renewable sources of energy. However, there are many more methods that are practical. There are now three major advances in technical practice that are going place. The first of them is based on something called an alkaline electrolyser cell, which has been utilized on an industrial scale ever since the 1920s. The Proton Exchange Membrane Electrolysis Cell is the name of the second approach, which is superior to the alkaline method in terms of its ability

to be versatile and the amount of space it takes up in comparison. The third kind is called a Solid Oxide Electrolysis Cell, and it functions at a greater temperature than the other two. Because a single cell has the ability to produce hydrogen from electricity as well as to produce electricity from hydrogen, with a highly satisfying efficiency of around 80%, it is a more recent approach that is still in the development process. However, it is very appealing and offers tremendous potential. This technological capability has not yet reached its full potential.

The European Green Deal, which lays out a strategy for making Europe the first climate-neutral continent by the year 2050 and includes hydrogen as a crucial component of the plan, was announced in 2019. The Green Deal is an initiative that was designed as a plan to build a society that is more equitable and to strengthen the economy of the EU via the development of green technologies and new ideas. The European Green Deal is proposing an increase in the GHG reduction target for 2030 from the present 40% to between 50-55%, with the ultimate goal of reaching net-zero greenhouse gas emissions by the year 2050. The European Union's Hydrogen Strategy outlines the steps that should be taken between the years 2020 and 2050 to advance the hydrogen economy across the EU. The European Union (EU) will provide financial assistance for the installation of at least 6 GW worth of renewable hydrogen electrolyzers during the first phase (2020-2024). During the second phase (2025-2030), the capacity of electrolyzers will expand to at least 40 GW, and it is anticipated that electrolyzers will be widely implemented in industries that are difficult to decarbonize by the year 2050. The Strategy forecasts that production of environmentally friendly hydrogen will increase to 1 Mt in 2024 and 10 Mt in 2030.

The last question "Can it be utilized in the near future to change the European transportation industry into a carbon neutral transportation sector?" There are various factors that need to be taken into consideration while talking about the transport sector as a whole. As there is currently a need for hydrogen and there are plans to scale up the production of green hydrogen, it is possible that the transportation industry will swiftly adopt green hydrogen during the next decade. Shipping and aviation, however, face a significantly different condition. Existing planes and boats may employ drop-in fuels, which are created from green hydrogen but still are nearly equal to jet fuel and methanol obtained from petroleum, with few changes. Furthermore, these fuels incorporate CO<sub>2</sub>, which must be captured and added to the

hydrogen before they can be burned; this reduces CO<sub>2</sub> emissions but does not solve the problem. Within the next few years, ships will be capable of switching to green ammonia, a carbon dioxide-free fuel created from green hydrogen and nitrogen from the air. However, engines and tanks will need to be upgraded, and green ammonia is substantially more expensive than fuel oil. Hydrogen or ammonia-powered aircraft are much further ahead, and they will be completely new aircraft that must be designed, manufactured, and sold to airlines in order to replace jet-fuel-powered aircraft that are obviously impractical by 2030. In this context, the rapid implementation of green jet fuel derived from a combination of green hydrogen and sustainable bioenergy is a viable option.

In conclusion, the general public's attitude toward hydrogen has been more positive in recent years; nonetheless, it is essential to keep a critical attitude and to keep in mind that hydrogen will also generate its fair share of effects and emissions. It is exhilarating to observe the extraordinary worldwide political momentum that is propelling the development of low-carbon hydrogen, with many innovative initiatives paving the way for this essential component of the energy revolution of the 21st century. Despite this, it is important to note that there is still a long way to go before low-carbon hydrogen can become a reality. Green hydrogen is the only viable option for decarbonizing many industries, including the transportation and mobility industries, and reducing the use of conventional fuels in these industries; which as a result, will help us get closer to our goal of reaching carbon neutrality in 2050.

## 7. References

Advantages & Disadvantages of Hydrogen Energy. (2021). Conserve energy in the future. [https://www.conserve-energy-future.com/advantages\\_disadvantages\\_hydrogenenergy.php](https://www.conserve-energy-future.com/advantages_disadvantages_hydrogenenergy.php)

Alternative Fuels Data Center: Hydrogen Production and Distribution. (2016). Alternative Fuels Data Center. [https://afdc.energy.gov/fuels/hydrogen\\_production.html](https://afdc.energy.gov/fuels/hydrogen_production.html)

Belmans, R. (2020). GREEN HYDROGEN: BRIDGING THE ENERGY TRANSITION IN AFRICA AND EUROPE. Africa-EU Energy Partnership. [https://africa-eu-energy-partnership.org/wp-content/uploads/2021/04/AEEP\\_Green-Hydrogen\\_Bridging-the-Energy-Transition-in-Africa-and-Europe\\_Final\\_For-Publication\\_2.pdf](https://africa-eu-energy-partnership.org/wp-content/uploads/2021/04/AEEP_Green-Hydrogen_Bridging-the-Energy-Transition-in-Africa-and-Europe_Final_For-Publication_2.pdf)

Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification. (2016, August 24). AGH. <http://home.agh.edu.pl/~czepir/pdf/2016JCP.pdf>

Carrier, M. (2022, April 22). Transport industry in Europe - statistics & facts. Statista. <https://www.statista.com/topics/3671/transportation-industry-in-europe/#topicOverview>

Ecological and Economic Evaluation of Hydrogen Production by Different Water Electrolysis Technologies. (2020, 8 12). Wiley online library. <https://onlinelibrary.wiley.com/doi/10.1002/cite.202000090>

Engineering Explained: 5 Reasons Why Hydrogen Cars Are Stupid - Fails. (2016). Car Throttle. <https://www.carthrottle.com/post/engineering-explained-5-reasons-why-hydrogen-cars-are-stupid/>

EUROPEAN HYDROGEN BACKBONE - Analysing future demand, supply, and transport of hydrogen. (2021, 06). Gas for Climate. [https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB\\_Analysing-the-future-demand-supply-and-transport-of-hydrogen\\_June-2021\\_v3.pdf](https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021_v3.pdf)

Forbes. (2020, June 6). Estimating The Carbon Footprint Of Hydrogen Production. <https://www.forbes.com/sites/rpapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/?sh=62808e6024bd>

The Future of Hydrogen – Analysis - IEA. (2019, 06). International Energy Agency. <https://www.iea.org/reports/the-future-of-hydrogen>

Global Transport and Climate Change. (2021). SLOCAT Transport and Climate Change Global Status Report. <https://tcc-gsr.com/wp-content/uploads/2021/06/1.1-Global-Transport-and-Climate-Change.pdf>

Global Transport Scenarios 2050. (2011). World Energy Council. [https://www.worldenergy.org/assets/downloads/wec\\_transport\\_scenarios\\_2050.pdf](https://www.worldenergy.org/assets/downloads/wec_transport_scenarios_2050.pdf)

Goodman, J. (2020, November 30). In-depth Q&A: Does the world need hydrogen to solve climate change? Carbon Brief. <https://www.carbonbrief.org/in-depth-qa-does-the-world-need-hydrogen-to-solve-climate-change/>

Hydrogen. (2022). Energy. [https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen\\_en](https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en)

Hydrogen Production and Uses. (2021, 11). World Nuclear Association. <https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx>

Hydrogen Production: Biomass-Derived Liquid Reforming. (2021). Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-derived-liquid-reforming>

Hydrogen Production: Biomass Gasification. (2021). Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification>

Hydrogen Production: Photoelectrochemical Water Splitting. (2022). Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-production-photoelectrochemical-water-splitting>

Hydrogen production through electrolysis. (2021). H2 Bulletin. <https://www.h2bulletin.com/knowledge/hydrogen-production-through-electrolysis/>

A hydrogen strategy for a climate-neutral Europe. (2020, 07 08). EUR-Lex. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301>

In focus: Renewable hydrogen to decarbonise the EU's energy system. (2022, November 15). European Commission. [https://ec.europa.eu/info/news/renewable-hydrogen-decarbonise-eus-energy-system-2022-nov-15\\_en](https://ec.europa.eu/info/news/renewable-hydrogen-decarbonise-eus-energy-system-2022-nov-15_en)

Louvet, L. (2021, June 30). Green hydrogen in the energy transition: a review. Aaltodoc. [https://aaltodoc.aalto.fi/bitstream/handle/123456789/109269/master\\_Louvet\\_Louis\\_2021.pdf?sequence=1&isAllowed=y](https://aaltodoc.aalto.fi/bitstream/handle/123456789/109269/master_Louvet_Louis_2021.pdf?sequence=1&isAllowed=y)

Mäkelä, M. (2021, April 4). Development of Green Hydrogen Economy and its Feasibility in Electricity Generation in Europe. Osuva. [https://osuva.uwasa.fi/bitstream/handle/10024/12442/UniVaasa\\_2021\\_Ma%CC%88kela%CC%88\\_Mikael.pdf?sequence=3&isAllowed=y](https://osuva.uwasa.fi/bitstream/handle/10024/12442/UniVaasa_2021_Ma%CC%88kela%CC%88_Mikael.pdf?sequence=3&isAllowed=y)

Mastronardo, E. (2021, May 14). Hydrogen Production by Solar Thermochemical Water-Splitting Cycle via a Beam Down Concentrator. Frontiers. <https://www.frontiersin.org/articles/10.3389/fenrg.2021.666191/full>

MSc Program Environmental Technology & International Affairs Hydrogen as a Potential Renewable and Secure Source for Energy Supply. (2019, January 17). MSc Program Environmental Technology & International Affairs Hydrogen as a Potential Renewable and Secure Source for Energy Supply.

[https://www.researchgate.net/publication/334233674\\_Hydrogen\\_as\\_a\\_Potential\\_Renewable\\_and\\_Secure\\_Source\\_for\\_Energy\\_Supply](https://www.researchgate.net/publication/334233674_Hydrogen_as_a_Potential_Renewable_and_Secure_Source_for_Energy_Supply)

Production of hydrogen - US Energy Information Administration. (2022, January 21). EIA. <https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php>

Rauch, R. (2018, 12). Hydrogen from biomass gasification. IEA Bioenergy. [https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie\\_IEA-final.pdf](https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf)

Smoot, G. (2022). What Is the Carbon Footprint of Diesel Fuel? A Life-Cycle Assessment. Impactful Ninja. <https://impactful.ninja/the-carbon-footprint-of-diesel-fuel/>

Smoot, G. (2022). What Is the Carbon Footprint of Fossil Fuels? A Life-Cycle Assessment. Impactful Ninja. <https://impactful.ninja/the-carbon-footprint-of-fossil-fuels/>

Smoot, G. (2022). What Is the Carbon Footprint of Gasoline? Here Are the Facts. Impactful Ninja. <https://impactful.ninja/the-carbon-footprint-of-gasoline/>

The study “Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans” has just been published! (2020, September 9). Trinomics. [https://trinomics.eu/fch\\_ju\\_study\\_hydrogen/](https://trinomics.eu/fch_ju_study_hydrogen/)

Tasić, D. (2021, January 8). A hydrogen strategy for a climate-neutral Europe. H2GreenTECH. <https://www.h2greentech.eu/a-hydrogen-strategy-for-a-climate-neutral-europe/>

Thomson, L. (2021, October 5). Region-Wise Evaluation of Green Hydrogen Production in Europe. AZoCleantech.com. <https://www.azocleantech.com/article.aspx?ArticleID=1332>

Transport Analysis IEA. (2022). International Energy Agency. <https://www.iea.org/reports/transport>

Transport statistics at regional level - Statistics Explained. (2022, October 14). European Commission.

[https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Transport\\_statistics\\_at\\_regional\\_level](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Transport_statistics_at_regional_level)

U.S Department of Energy. (2016, April). Hydrogen Production.

[https://www.energy.gov/sites/prod/files/2016/07/f33/fcto\\_hydrogen\\_production\\_fs.pdf](https://www.energy.gov/sites/prod/files/2016/07/f33/fcto_hydrogen_production_fs.pdf)

What is green hydrogen? An expert explains its benefits. (2021, December 21). The World Economic Forum.

<https://www.weforum.org/agenda/2021/12/what-is-green-hydrogen-expert-explains-benefits/>

Wilkinson, S. (2022, 01 31). Hydrogen fuel cells: do hydrogen cars have a future? Auto Express.

<https://www.autoexpress.co.uk/electric-cars/93180/hydrogen-fuel-cells-do-hydrogen-cars-have-future>

Wolf, A., & Zander, N. (2021). Green Hydrogen in Europe: Do Strategies Meet Expectations? Intereconomics.

<https://www.intereconomics.eu/contents/year/2021/number/6/article/green-hydrogen-in-europe-do-strategies-meet-expectations.html>