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Evaluating the Feasibility and Environmental Impact of Alternative Fuels for Sustainable Operations of RCG Reach Stackers at Four European Locations

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Declaration of Authorship

I, Antonia BIEBIGHÄUSER, hereby declare that the work presented in this dissertation, titled, "Evaluating the Feasibility and Environmental Impact of Alternative Fuels for Sustainable Operations of RCG Reach Stackers at Four European Locations", is entirely my own original work. I affirm that it has not been fully or partially submitted previously in any other Italian or foreign university for assessment purposes.

I further confirm that the content of this dissertation is the result of my own intellectual endeavors, and I have appropriately cited all sources used. This work does not infringe upon the intellectual property rights of any third party, and its contents do not constitute plagiarism.

I understand the consequences of submitting work that is not my own and affirm the honesty and integrity of this academic contribution.

Signed: Antonia Biebighäuser

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Abstract

Departement of Chemical Sciences

MSc: Sustainable Chemistry and Technologies for Circular Economy

Evaluating the Feasibility and Environmental Impact of Alternative Fuels for Sustainable Operations of RCG Reach Stackers at Four European Locations

by Antonia BIEBIGHÄUSER

This thesis evaluates the feasibility and environmental impact of alternative fuels - specifically hydrogen, biofuels, and synthetic fuels - for sustainable operations of Rail Cargo Group (RCG) reach stackers, located in Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK). The study addresses the urgent need to transition from fossil fuels due to their finite nature, geopolitical risks, and significant contribution to climate change. Through a comprehensive review of scientific literature, industry reports, and government publications, the research assesses the production processes, availability, cost-effectiveness, political support, and technological readiness of these alternative fuels. A detailed case study of RCG reach stackers provides practical insights into the application of these fuels. The findings indicate that while hydrogen and synthetic fuels offer significant environmental benefits, their high production costs and infrastructure requirements pose challenges. Biofuels, particularly second and third generation, present a more immediate and economically viable solution, though they require careful management to avoid adverse environmental impacts. The study concludes with recommendations for integrating these alternative fuels into existing energy infrastructures, contributing to global efforts to mitigate climate change and enhance energy security.

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Evaluating the Feasibility and Environmental Impact of Alternative Fuels for Sustainable Operations of RCG Reach Stackers at Four European Locations

Antonia BIEBIGHÄUSER

Chapter 1

Introduction

1.1 Context and Background - The Integration of Fossil Fuels into Today's Society

Fossil fuels - coal, oil, and natural gas - have been the foundation of global energy production and economic development for over a century, transforming societies and shaping the modern world. The first widespread use of fossil fuels can be traced back to the 1770s, when the English entrepreneur, Richard Arkwright, pioneered an innovation in textile manufacturing that replaced traditional hand-operated spinning wheels with a mechanized steam-powered textile mill [1]. A spinning process that had taken several days or even weeks using manual methods was replaced by mechanized spinning machines, that fundamentally altered the textile industry, by enhancing efficiency and productivity. This milestone was just one of the many significant advancements in technology, manufacturing, and societal structures during the Industrial Revolution in the 18th and 19th century. Central to most of the technological transformation at that time were steam engines - revolutionary machines that utilize the power of steam to drive mechanical processes, while allowing for efficient and reliable power generation [2]. These engines were initially fueled solely by coal, due to its easy accessibility in many industrialized regions (e.g., Britain) and high energy density compared to other forms of traditional energy sources like firewood [3]. But as technology advanced and exploration expanded, oil and natural gas were discovered as valuable alternatives, due to their liquid and gaseous forms, respectively, as well as their combustion efficiency in certain types of engines.

Overall, the utilization of fossil fuels underwent a notable transition during the Industrial Revolution, escalating from a mere 5 % to a substantial 80 % of the total energy consumption in just 150 years [4]. This marked a significant shift, shaping a world where fossil fuels became an integral part of our daily lives [5].

1.2 Objectives and Approach - The Need for Alternative Fuels

Despite their historical significance, the reliance on fossil fuels presents several critical challenges. Firstly, fossil fuels are finite and non-renewable, with reserves depleting faster than new ones are discovered [6]. The concept of 'peak oil', introduced by Marion King Hubbert, suggests that the rate of fossil fuel production will eventually reach a peak and then decline, leading to higher extraction costs and potential economic instability [6, 7, 8]. Secondly, the geopolitical landscape of fossil fuel reserves is fraught with instability, as evidenced by the recent energy crisis in Europe following the conflict between Russia and Ukraine [9]. This crisis highlighted the vulnerabilities of relying on a single supplier and underscored the need for energy diversification [10, 11]. Lastly, the environmental impact of fossil fuels, particularly their contribution to climate change through greenhouse gas emissions, is a pressing global concern. The combustion of fossil fuels is a major source of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), all of which significantly contribute to global warming and climate change [12, 13, 14]. The urgency to address these environmental challenges has never been greater, as the world grapples with the consequences of climate change, including extreme weather events, rising sea levels, and loss of biodiversity.

Recognizing these challenges, the primary objective of this thesis is to identify and evaluate the potential of alternative fuels - specifically hydrogen, biofuels, and synthetic fuels - as replacements for fossil fuels. The study will explore the production processes, availability, overall cost-effectiveness, political support, and technological readiness of these fuels, along with their individual environmental impacts. The findings will be illustrated through a case study involving diesel-powered reach stackers operated by the Rail Cargo Group (RCG).

The objectives of this research are to:

1. Analyze the potential of hydrogen, biofuels, and synthetic fuels.
2. Evaluate their environmental and economic implications.
3. Propose a strategy for integrating these fuels into the existing energy infrastructure, using RCG reach stackers as a case study.

This research is significant as it addresses the urgent need to transition from fossil fuels to alternative energy sources, thereby contributing to global efforts to mitigate climate change and enhance energy security. By focusing on the practical application of alternative fuels in the operation of RCG reach stackers, this study provides valuable insights into the feasibility and environmental impact of these fuels. The findings and recommendations from this research have the ability to support and influence policy decisions and strategic planning for the integration of alternative fuels into the existing energy infrastructure.

The subsequent chapter delves into the state of the problem, including an assessment of the finite nature of fossil fuels and the concept of ’peak oil’ introduced by Marion King Hubbert. It also addresses the geopolitical and environmental ramifications of fossil fuel dependence, highlighting the urgent need for energy diversification and the transition to alternative fuels. The methodology employed for the following chapter involves a comprehensive review of scientific literature, industry reports, and government publications, combined with qualitative and quantitative analyses to assess the environmental and economic implications of alternative fuels.

Chapter 2

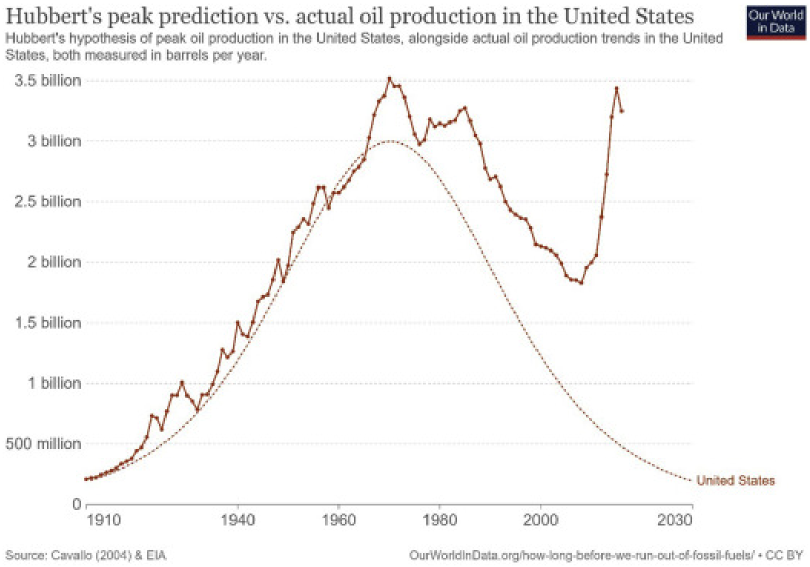
State of the Problem - Current Challenges and Implications of Fossil Fuel Dependence

2.1 Formation, Peak, and Depletion of Fossil Fuels

One of the primary problems stemming from society's heavy reliance on fossil fuels is the fundamental reality that these energy sources are finite and non-renewable [15]. While the three primary fossil fuels - coal, oil, and natural gas - are all hydrocarbons, created through the decomposition and compression of ancient organic matter, the exact type of fossil fuels that accumulates depends on the specific conditions and environments in which this material was buried and transformed. Understanding the unique formation pathways for each fossil fuel is crucial for appreciating the finite nature of these energy reserves.

Oil and natural gas are primarily produced in warm and shallow oceans, where organic matter (e.g., plankton) falls to the ocean floor and mixes with inorganic material (e.g., clay minerals, carbonates, Ca- and Fe-sulfates, and Fe-oxides and -hydroxides), that enters the ocean through rivers [16]. The transition from this sediment to oil or natural gas is determined by the physical conditions of the environment. Extreme hot temperatures and anoxic conditions favor natural gas formation, whereas oil is formed in less hot temperatures [16]. If the temperature is, however, too cold, the plankton will remain trapped as kerogen (i.e., solid, insoluble organic matter found in sedimentary rock).

Coal, on the other hand, begins its formation in swampy wetlands where the rapid production of plant matter outpaces its decomposition [17]. This organic matter accumulates and gets buried, forming layers that eventually turn into coal via two main phases: peatification and coalification [18]. As peat (i.e., spongy accumulation of partially decayed vegetation) gets deeply buried, water and other compounds are squeezed out due to increasing pressure, forming the lowest quality of coal, lignite. Continued burial, resulting in increasing pressures and temperatures, transforms this lignite into higher quality 'black coals' such as (sub-)bituminous coal, and finally, the highest quality anthracite coal [17, 18].


Hubbert's peak prediction vs. actual oil production in the United States

Hubbert's hypothesis of peak oil production in the United States, alongside actual oil production trends in the United States, both measured in barrels per year.

Source: Cavallo (2004) & EIA

OurWorldInData.org/how-long-before-we-run-out-of-fossil-fuels/ • CC BY

FIGURE 2.1: Comparison of Hubbert's peak prediction of oil production in the United States versus the actual oil production trends, as measured in barrels per year. The thin line represents Hubbert's hypothesis, while the thick line shows the real-world oil production data from 1910 to the present day. Source: Cavallo (2004) & EIA [21]. Retrieved from OurWorldInData.org

The formation of these resources takes millions of years, a process that was first theorized by the American geophysicist Marion King Hubbert and subsequently conceptualized in his 'peak oil theory', also known as 'Hubbert's peak theory'. Although the model has been invented only for oil, it can be applied to many resources, including all fossil fuels. It suggests that for any given geographical area, the rate of fossil fuel production will eventually reach a peak and then enter a terminal decline, following a roughly bell-shaped curve [7]. In the traditional vision of peak oil, the production decline accelerates as the cost of extracting new reserves grows. If new reserves are not brought online more rapidly than the existing reserves draw down, then peak fuel has been reached.

Upon the formulation of his theory in 1956, Hubbert predicted that global peak oil would occur in the early 2000s and then enter into decline [19]. However, this prediction has been criticized for not accounting for technological advancements that could enable access to previously untapped oil fields, nor considering the potential decrease in demand for fossil fuels due to climate action policies [8, 20]. This has become apparent in the early 2000s in the United States (US) (see Figure 2.1), when the actual production trend started to deviate from Hubbert's hypothesis and a sharp increase in actual oil production was noted [21]. But despite increasing discoveries, as well as improvements in fuel extraction methods, the time will come when the recyclable rate of fossil fuels will begin to decline until it reaches its end point. A reevaluation of peak oil by the International Energy Agency (IEA) and Organization of the Petroleum Exporting Countries (OPEC) forecasts global peak production to be reached in 2028 and 2045, respectively [22, 23].

While the exact year of peak fuel varies, it is acknowledged that the rate of discovery of new fuel reserves has been declining. This is due to the fact that easily accessible fuel fields have already been found, and new discoveries are often in more remote and challenging locations [24, 25]. Furthermore, the cost of exploration and extraction has increased, making it less economically viable to turn resources into reserves [1]. Contrarily, the rate of consumption has been increasing, suggesting that we are likely to run out of fossil fuels at some point in the future [6].

If peak oil is reached due to the exhaustion of reserves, the consequences will be higher oil prices and a shift towards unconventional oil sources (e.g., oil extracted from tar sands or oil shale) public unrest and dissatisfaction with government policies, as well as geopolitical tensions and conflicts over remaining oil resources [26, 27]. If peak oil, however is reached because of successful adoption to alternative sources, the above-mentioned economic, social, and political consequences can be avoided.

Recognizing the finite nature of fossil fuels and the urgent need for alternatives to avoid depletion and its devastating consequences, it becomes apparent that diversifying energy sources is essential for reaching peak fuel on our own terms. This approach not only empowers society to reduce its reliance on a finite and depleting resource, but also serves as a strategic method to enhance energy security, which will be discussed in the following sub-chapter.

2.2 Energy security due to diversification of energy sources and elevation of geopolitical tensions

Traditionally defined by the International Energy Agency (IEA) as the '*uninterrupted availability of energy sources at an affordable price*', the concept of '*energy security*' has evolved to encompass a balance between local energy supply and demand, as well as the intricate dynamics of political relations and development rights [28]. The reliance on fossil fuels, despite their advantages such as high energy density, versatile usage, and economic benefits, poses significant challenges to energy security. This has been made painfully clear, when Russia invaded Ukraine in February 2022, with catastrophic effects not only on human lives but also on international energy economies [11]. Being the world's largest exporter of fossil fuels, Russia weaponized energy exports in an attempt to drive up commodity prices and sow uncertainty [9]. Consequently, Europe has been experiencing the biggest energy crisis in decades with natural gas supplies from Russia via Nord Stream 1 having come to a complete halt in August 2022 in Germany [29]. In response to these challenges, Europe sought to replace Russian gas, by bidding up prices of US, Australian and Qatari ship-borne

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[1] Resources refer to the total amount of a particular fossil fuel that exists in the Earth's crust, while reserves refer to the amount of that resource that can be extracted using current technology and at current costs. It is possible for a resource to be very large, but if it is not economically feasible to extract it, it cannot be considered a reserve

liquefied natural gas (LNG), raising prices and diverting supply away from traditional LNG customers in Asia [10]. Because gas frequently sets the price at which electricity is sold, power prices soared as well [29]. Overall, Europe was spared from rationing energy, due to a mild winter, lower-than-expected demand, and filled storage sites from non-Russian supplies, especially Norway and the Netherlands [11]. This crisis did however amplify the need for Europe to reduce its dependence on a single supplier and to diversify its energy sources. Transitioning to a more diverse portfolio of energy sources, including renewable alternatives, would help insulate the European Union (EU) from the geopolitical volatility that can impact fossil fuel markets.

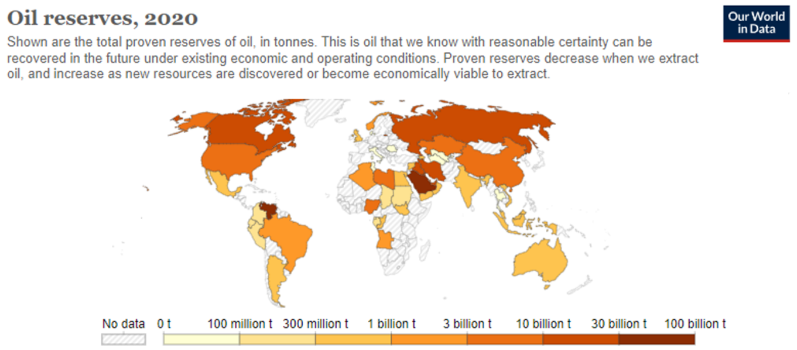
To overcome these challenges, the European Union (EU) released the Versailles Declaration in March 2022, with the goal to phase out Russian fossil fuel imports '*as soon as possible*' [11]. The overall theme of these strategies centers around enhancing and transforming the EU's energy landscape [30]. This includes transitioning away from fossil fuels, diversifying energy sources and supply routes, advancing renewable energy sources and their related infrastructure, strengthening energy networks and security measures, improving energy efficiency, and promoting sustainable consumption patterns. A key component and comprehensive strategy of the EU's response to the Versailles Declaration is the REPowerEU plan, which was formulated by the European Commission (EC) and released in May 2022 [31, 32, 33]. The plan's measures include

- Energy savings (i.e., increasing the EU's 2030 binding energy saving target to 13 %, up from 9 % in the Energy Efficiency Directive) [31]
- Diversification of energy imports (i.e., establishing agreements with other countries for pipeline imports and investing in common purchase of LNG) [31, 32]
- And the acceleration of Europe's clean energy transition to a 45 % renewable energy share across the EU by 2030 [33]

As a result of the REPowerEU plan, the European Union has successfully reduced its dependency on Russian gas. While there is no clear consensus on the exact amount of Russian gas currently being imported, the International Energy Agency (IEA) reported a significant decrease in imports between August 2021 and September 2022 [31]. This indicates a successful shift away from Russian gas and a diversification of the EU's energy supply. Nevertheless, countries such as Hungary and Austria remain heavily reliant on Russian gas.

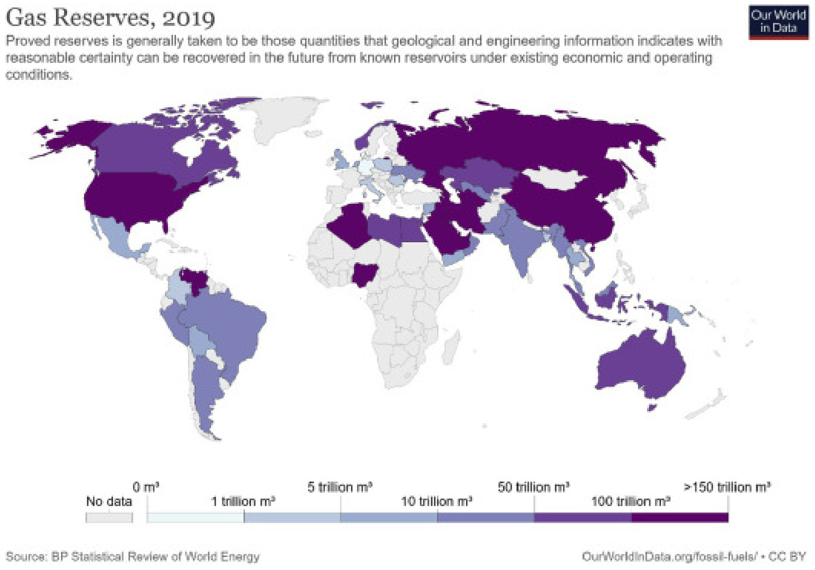
The security of the EU's energy system, however, remains a complex issue. Despite the notable successes in diversification efforts under the REPowerEU plan, several challenges persist in ensuring a stable and secure energy supply. One significant challenge is the anticipated increase in electricity demand, projected to rise by 12 - 26 % by 2040 [34].

To further understand the EU's predicament regarding energy security, it is essential to examine the global distribution of fossil fuel reserves. These reserves are


Oil reserves, 2020

Shown are the total proven reserves of oil, in tonnes. This is oil that we know with reasonable certainty can be recovered in the future under existing economic and operating conditions. Proven reserves decrease when we extract oil, and increase as new resources are discovered or become economically viable to extract.

FIGURE 2.2: The global distribution of proven oil reserves as of 2020, using a color gradient to represent the quantity of reserves in million tonnes. The darkest shades indicate countries with the largest oil reserves, exceeding 100 billion tonnes, while lighter shades represent countries with smaller reserves. The data, sourced from OurWorldInData.org [35], highlights the critical role of oil in the global energy landscape and its concentration in specific regions.


Gas Reserves, 2019

Proved reserves is generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions.

Source: BP Statistical Review of World Energy

OurWorldInData.org/fossil-fuels/ • CC BY

FIGURE 2.3: The global distribution of proven natural gas reserves as of 2019, with a color-coded legend indicating the volume of reserves in trillion cubic meters. The darkest shades of purple denote countries with the largest gas reserves, exceeding 150 trillion cubic meters, while lighter shades represent countries with smaller reserves. The data, sourced from OurWorldInData.org [35], visually conveys the strategic importance of natural gas as an energy source and its uneven geographical distribution.

unevenly distributed across the world, with the majority located in regions often characterized by geopolitical instability. For instance, countries in the Middle East, Russia, and parts of Africa possess substantial oil, natural gas, and coal reserves (see Figure 2.2, Figure 2.3, and Figure 2.4, obtained from OurWorldInData.org [35]), yet they frequently experience political turmoil, leading to unpredictable supply disruptions [36]. In contrast, the EU's own reverses of coal, oil, and natural gas are relatively limited. Only a few countries, such as the Netherlands (gas), Italy (gas), Germany (coal) and Poland (gas and coal), having (significant) domestic production capabilities [35, 36].

This global imbalance in fossil fuel distribution implies that the EU must rely heavily on imports to meet its energy needs. Such dependence subjects the EU to multifaceted risks: price volatility, potential supply disruptions, and the diplomatic intricacies of engaging with supplier nations whose political values or stability may

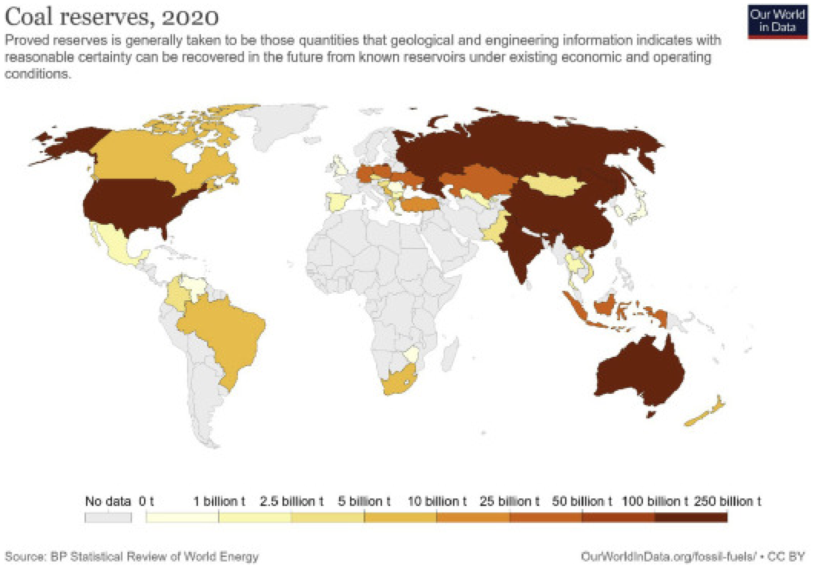


FIGURE 2.4: The global distribution of proven coal reserves as of 2020, using a color-coded scale to represent the quantity of reserves in billion tonnes. The darkest shades of brown indicate countries with the largest coal reserves, exceeding 250 billion tonnes, while lighter shades and yellow represent countries with smaller reserves, ranging from less than 1 billion to 25 billion tonnes. The data, sourced from OurWorldInData.org [35], provides insights into the potential energy security and supply dynamics of different regions associated with coal extraction and utilization.

diverge from those of the EU. Consequently, the EU's energy security is inextricably linked to the geopolitical landscape of energy-rich regions, underscoring the urgency for the EU to diversify its energy sources and bolster its resilience against external shocks.

In response to these geopolitical challenges and due to economic, technological, and environmental shifts, the EU's landscape has been undergoing significant changes over the last 30 years. These include the awareness of environmental impact of fossil fuels, increased efficiency of renewable energy sources such as wind, solar, and biomass, fluctuations of oil and gas prices, and concerns over energy security.

For 2020, the composition of EU's energy mix is illustrated in Figure 2.5. The central segment of the Figure is divided into two primary categories: 'Imported' and 'Domestic' energy sources. Overall, 50 - 60 % of the EU's gross energy requirements have been imported, as domestic production combined with adjustments in reserves accounted for only 40 - 50 % of its consumption requirements [37, 38].

Surrounding this central segment are various colored segments representing specific energy sources. Renewable energy sources constituted the largest segment to the domestic energy mix, with 17.4 %, followed by nuclear energy at 12.7 % [37]. Fossil fuels - oil, coal, and natural gas - contributed 9.66 %, 5.67 %, and 1.87 % respectively [37].

Oil was the predominant energy source in the EU's 2020 energy portfolio, ranking third in terms of domestic production and first as an imported commodity [37, 38]. Having a look at the outermost layer of the chart, Russia emerged as the principal supplier of crude oil, providing more than the combined total of the next three

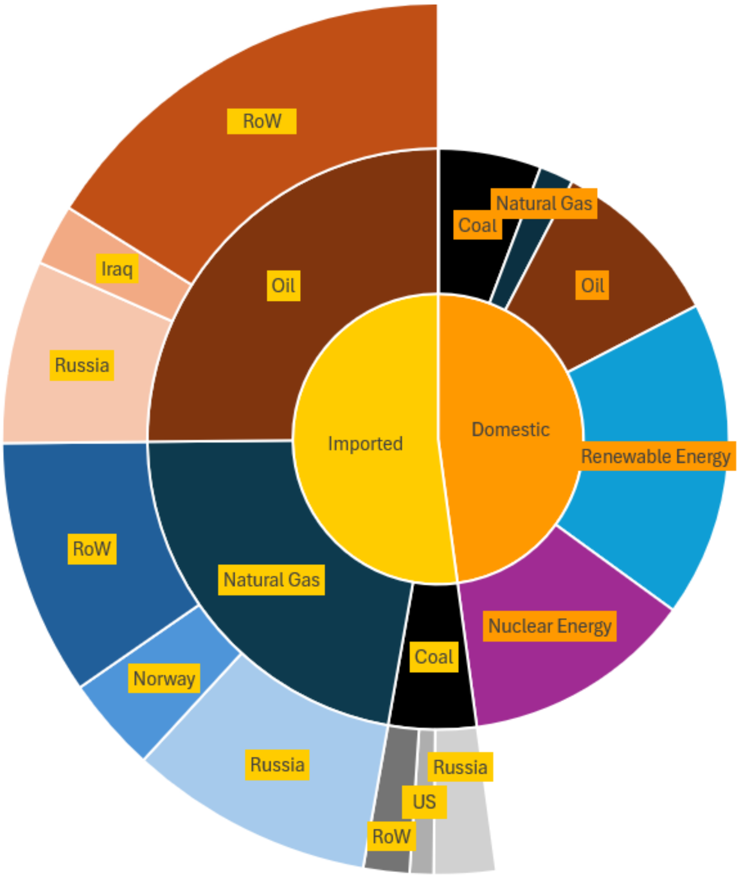


FIGURE 2.5: Composition of the European Union's (EU) energy mix, highlighting the proportions of different energy sources and their origins. The central segment of the chart is divided into two primary categories: 'Imported' and 'Domestic' energy sources. The second segment represents specific energy sources, including 'Oil', 'Natural Gas', 'Coal', 'Renewable Energy', and 'Nuclear Energy'. The outermost layer indicates the geographic origins of the imported energy, including 'Russia', 'Iraq', 'Norway', the 'United States' (US), and 'RoW' (Rest of World). Data compiled from multiple sources: [37, 38, 39, 40, 41]

contributing countries [37]. Specifically, Russia supplied 27 % of the imported crude oil, followed by Iraq at 9.0 %, Nigeria at 7.9 %, and Saudi Arabia at 7.7 % [38].

The majority of the EU's imported natural gas in 2020 was sourced from Russia, primarily through the Nord Stream pipeline series, accounting for 41 % of imports [37, 39]. Norway was the second-largest supplier, contributing 16.2 %, with the remainder sourced from various other countries including Algeria (7.6 %) and Qatar (5.2 %) [37, 38, 39].

Despite plans by most EU member states to phase out coal-fired power plants by 2030, coal remains a significant part of the energy mix [40]. While the majority of coal consumed was domestically produced, about 47 % of the coal imports in 2020 originated from Russia [37]. Other major suppliers included the United States (17.7 %), Australia (13.7 %), Colombia (8.2 %), and South Africa (2.8 %) [37, 38].

Relying heavily on energy imports from countries such as Russia, Iraq, Nigeria, and Saudi Arabia presents significant geopolitical risks. These nations, while rich in fossil fuel reserves, are often embroiled in political instability or are at the center of international tensions, which can lead to unpredictable fluctuations in energy supply and prices [41]. Although some energy imports come from more stable regions like Norway and the U.S., these sources constitute only a minor portion of the total imports [37]. This underscores the urgency for EU member states to strive for energy independence. One viable pathway to achieving this is through the development and expansion of renewable energy sources.

In recent years, there has been a notable acceleration in the development of renewable energy technologies within the EU [38]. Investments in solar, wind, hydro, and bioenergy have surged, driven by both technological advancements and supportive policy frameworks. The European Green Deal, for instance, aims to make Europe the first climate-neutral continent by 2050, a goal that hinges significantly on ramping up renewable energy production and consumption [31, 32, 33]. Looking ahead, the outlook for energy security among EU member states appears increasingly robust. With continued investments and innovation in renewable energies, coupled with a gradual reduction in dependency on external fossil fuel supplies, the EU is well-positioned to enhance its energy sovereignty and resilience in the coming years.

Furthermore, by transitioning away from fossil fuels, countries can significantly lower their carbon emissions, thereby contributing to global efforts to mitigate climate change. This dual benefit not only strengthens European energy independence but also supports worldwide environmental sustainability, which will be explained in great detail in the following chapter.

2.3 Climate Change

The third and last argument on why we need alternative fuels to fossil fuels is a widely spread topic. 'Climate change, anthropogenic emissions, global warming, greenhouse gases' - these terms have become increasingly prevalent in the 21st century, dominating headlines and shaping global discourse. These terms are not just buzzwords but represent a profound shift in our planet's climate system [42].

The Earth's climate has been subject to natural cycles of change over millions of years, with carbon dioxide (CO_2) concentrations in the atmosphere playing a significant role in these fluctuations (see Figure 2.6). Natural increases in CO_2 concentrations due to volcanic eruptions and solar radiation fluctuations have periodically warmed the Earth's temperature during ice age cycles over the past million years and more. These warm episodes, known as interglacials, began with a small increase in incoming sunlight in the Northern Hemisphere due to variations in the Earth's orbit around the Sun and its axis of rotation, known as Milankovitch cycles [43]. As the Earth warms, various feedback mechanisms come into play that naturally increase CO_2 concentrations in the atmosphere, such as the increased release of CO_2 from the oceans [43]. Historically, these natural CO_2 concentrations have fluctuated between 175 ppm during glacial maxima (coldest periods) and 280 ppm during interglacials (warm periods) [44, 45]. Around 11.700 years ago, the last glacial maximum was recorded with a minimal atmospheric CO_2 concentration of 180 ppm, as

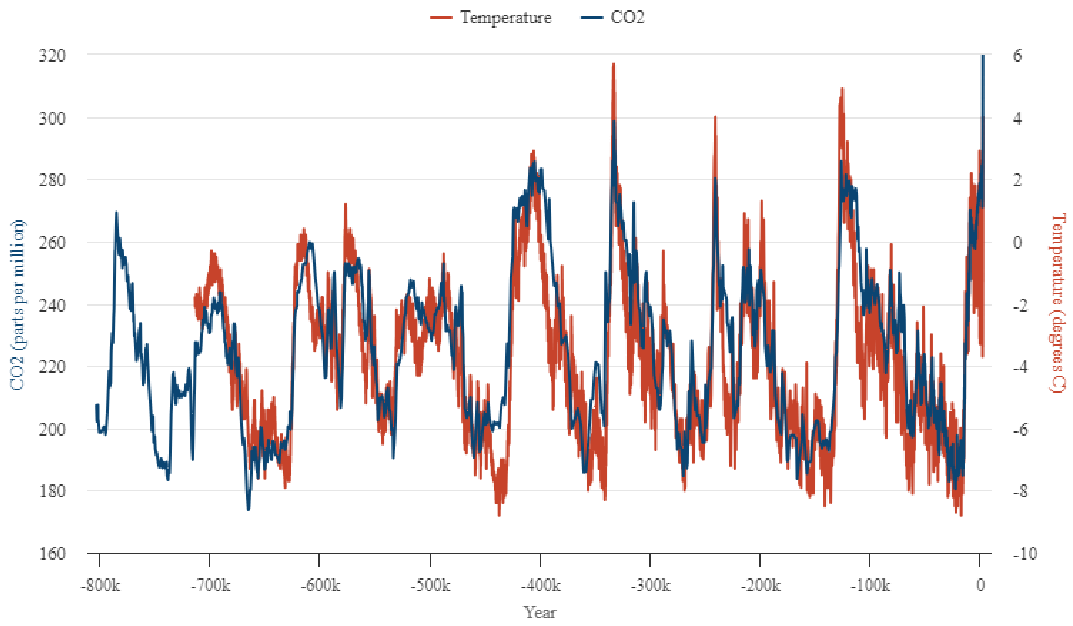


FIGURE 2.6: The graph illustrates the correlation between atmospheric carbon dioxide (CO_2) concentrations and global temperature variations over the past 800,000 years. The x-axis represents the timeline in years, extending from 800,000 years ago to the present, while the y-axes display the CO_2 levels in parts per million (ppm) on the left and temperature deviations in degrees Celsius on the right. The red line denotes temperature fluctuations, and the blue line indicates CO_2 concentrations. Retrieved from CarbonBrief [43].

depicted in Figure 2.6 and the transition to a warmer climate with the beginning of the Holocene occurred. It was not until the industrial ear, specifically in the mid-20th century, that atmospheric CO_2 concentrations exceeded 300 ppm for the first time in the last 800.000 years, due to human activities like the burning of fossil fuels, deforestation, and land-use changes.

Climate change is therefore a complex phenomenon that is characterized by both natural and anthropogenic (i.e., human-induced) factors. Since the 1950s, however, the increase in CO_2 concentrations and with it global temperatures have predominantly been driven by anthropogenic climate change, far outweighing the effects of natural CO_2 increases [42].

In 2024, a record-high of 420 ppm in atmospheric CO_2 has been recorded [42]. While 420 ppm might seem small in the context of numbers (being just 0.042 % of the atmospheric molecules), its impact on Earth's climate system is profound, as it represents a rapid shift in atmospheric conditions that historically have taken thousands of years to develop.

As the world grapples with the consequences of this rapid shift in atmospheric conditions, it becomes increasingly crucial to explore the scientific foundations and historical context of this phenomenon. The next sub-chapter will delve into the discovery of the anthropogenic greenhouse effect, tracing its origins and the growing body of evidence that links human activities to the observed changes in Earth's temperature.

2.3.1 The Dawn of Climate Awareness: Eunice Foote to the IPCC

In 1856, the amateur scientist Eunice Newton Foote first demonstrated that gases can absorb heat, by placing cylinders filled with different gaseous mixtures (i.e., moist air, dry air, carbon dioxide, oxygen, and hydrogen) in the sun and measuring the change in temperature over time [46]. She noted that the cylinder containing pure carbon dioxide warmed the most and was holding the heat the longest - even after the sun had set. With the following words she introduced the world to a concept that would become the single biggest threat to life on Earth in the 21st century:

> *"An atmosphere of that gas [carbon dioxide] would give to our Earth a high temperature"*

Unfortunately, her work was overlooked at the time due to societal norms and gender biases [46]. Three years later, in 1859, the male Irish scientist John Tyndall demonstrated in another experiment, that carbon dioxide and water vapor absorb heat in the form of infrared radiation [47]. He stated:

> *"Thus the atmosphere admits of the entrance of the solar heat; but checks its exit, and the result is a tendency to accumulate heat at the surface of the planet."*

This discovery made him known as 'the man that discovered the greenhouse gas effect', describing the natural process that concerns the characteristics of certain gases in the Earth's atmosphere that trap heat from the sun and prevent it from escaping back into space [48, 49]. While essential for life on Earth, human activities have amplified this natural process, leading to an increase in global warming [42].

This amplification of the greenhouse effect, often referred to as the enhanced or anthropogenic greenhouse effect, was first quantified in 1896 by the Swedish scientist Svante Arrhenius. He researched the changes in the concentration of carbon dioxide in the atmosphere on the temperature of the Earth's surface and described his observations as follows [50]:

> *"If [...] the quantity of carbonic acid [i.e., carbon dioxide dissolved in water] in the air is increased, the temperature of the Earth's surface increases. [...] It is found that this temperature variation amounts to the following values: If the carbonic acid content rises to 1.5 [relative to the time of discovery, the Earth's temperature will experience an increase of] +3.4 °C, if it rises to 2, +5.7 °C, and if it rises to 3, +8.4 °C"*

Luckily his quantification was not accurate and scientist now estimate that the doubling of CO_2 levels compared to pre-industrial level (280ppm) will raise temperatures by *only* 2-3 °C (and not 5-6 °C as Svante Arrhenius predicted) [42, 51].

In the late 1950s, almost 100 years after the first discovery of the greenhouse effect, physicist Gilbert Plass and other scientist in the US began warning government officials about the potential seriousness of greenhouse warming, a concern that was initially largely ignored [51]. Subsequently, researcher determined historic CO_2 levels through analysing trapped air in Arctic ice and reconstructed the historic CO_2 concentrations seen in Figure 2.6 [43].

In 2023, the Intergovernmental Panel on Climate Change (IPCC) released their Sixth Assessment Report (AR6) [42], which estimated that the global surface temperature had risen by 1.07 °C from the latter half of the 19th century through the first two decades of the 21st century [52]. This rise in temperature has led to significant changes in the Earth's climate system, including extreme alterations in the hydrological cycle, leading to heatwaves, droughts, flooding, and storm severity, as well as an increase in sea levels, ocean acidifications, and many more devastating consequences for the environment. It was also concluded, that this increase in temperature is largely attributed to human activities that release greenhouse gases into the air, altering the Earth's atmospheric composition [42, 52]. To comprehend the mechanisms and impacts of current climate change, a closer look is paid at the changes in the composition of Earth's atmosphere over the last millions of years.

2.3.2 The Evolution and Dynamics of Earth's Atmosphere: Composition and Climate Impact

The composition of Earth's atmosphere has undergone significant changes, since the first recording of life, 4.5 billion years ago. Initially, during the Precambrian period (4.5 billion to 540 million years ago) the atmosphere was likely composed of volcanic gases like water vapor (H_2O), carbon dioxide (CO_2), and ammonia (NH_3), with virtually no free oxygen (O_2) [53].

A major shift occurred with the proliferation of land plants around 540 million years ago, which led to a significant increase in atmospheric oxygen. This rise in oxygen levels, reaching up to 35% by volume, facilitated the formation of Earth's protective ozone layer and supported the development of complex life forms [54]. However, this period of high oxygen levels ended around 250 million years ago due to significant volcanic activity, which released vast amounts of CO_2 and methane (CH_4), causing extreme global warming, severe environmental stress, and mass extinctions [55].

During the Mesozoic Era (250 million to 65 million years ago), characterized by the dominance of dinosaurs, CO_2 levels fluctuated due to variations in solar radiation, generally resulting in warmer global temperatures than today [55, 56]. The subsequent Cenozoic Era, which began 65 million years ago and continues to the present, started with a relatively warm climate that gradually cooled [57, 58]. This cooling was supported by the formation of Antarctic ice sheets about 34 million years ago, which enabled the evolution of mammals and the expansion of grasslands, influencing the development of human ancestors [57, 58].

Today, the Earth's atmosphere is primarily composed of nitrogen (78 %) and oxygen (21 %). The remaining 1 % consists of trace gases, including carbon dioxide,

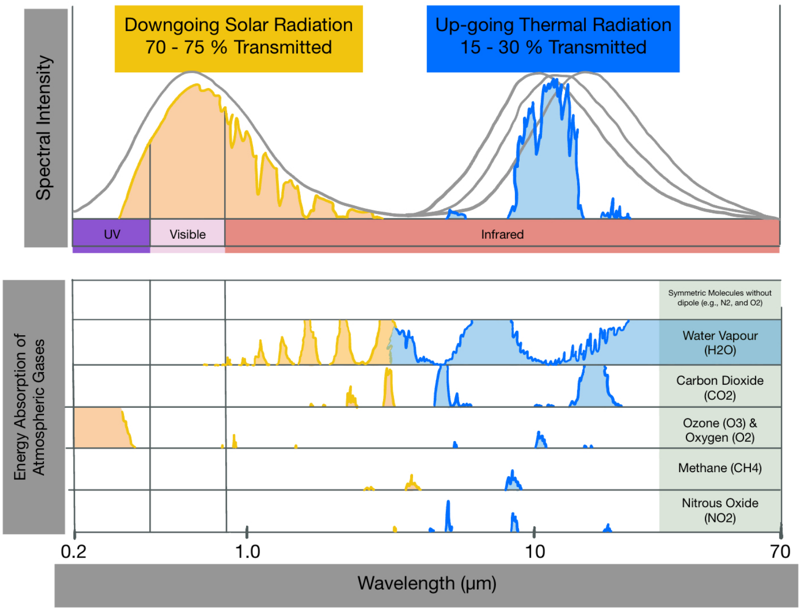


FIGURE 2.7: Comprehensive diagram depicting the down-going solar radiation (yellow shaded area) and the up-going thermal radiation (blue shaded area) in the upper segment. The lower segment details the distinct absorption bands of various atmospheric gases, including water vapor (HO), carbon dioxide (CO), ozone (O), oxygen (O), methane (CH), and nitrous oxide (NO), which influences the transmission of thermal radiation through the atmosphere. Primary information used to construct this Figure was retrieved from Climate Science Investigation NASA [63].

neon, helium, and methane, along with varying concentrations of water vapor. This composition plays a crucial role in supporting life as we know it. Apart from providing the necessary gases for respiration and protecting against harmful solar radiation, the composition of Earth's atmosphere also helps maintain a stable climate, as it limits daily temperature fluctuations by trapping heat in the atmosphere, leading to a current average of 14 °C [59, 60, 61].

The physical mechanisms behind this phenomenon, known as the greenhouse effect, will be explained in the following subchapter.

The Greenhouse Effect Explained

The greenhouse effect is a fundamental atmospheric process that warms the Earth's surface. It involves the absorption and re-emission of infrared radiation by greenhouse gases in the Earth's atmosphere, leading to an increase in surface and lower atmospheric temperatures [62]. This effect is crucial for maintaining the Earth's temperature at a level that can support life.

The primary mechanism of the greenhouse effect is the absorption of Earth's infrared radiation by greenhouse gases [62]. This process is illustrated in a two-part schematic diagram, depicted in Figure 2.7. The upper section of the diagram presents the spectral intensity, which refers to the percentage of solar radiation transmitted directly to the Earth's surface (yellow in Figure 2.7), peaking in the visible range, and the percentage of up-going thermal radiation transmitted back into space (blue in Figure 2.7), which is broader and of lower intensity [64, 63]. The x-axis represents wavelengths in microns, ranging from 0.2 to 70 microns, covering the ultraviolet, visible, near-infrared, and infrared regions of the electromagnetic spectrum, while the y-axis on the top graph indicates the spectral intensity.

The lower section displays the patterns of energy absorption by various atmospheric (greenhouse) gases at specific wavelengths, influencing the balance between radiation absorption and transmission. O and O exhibit high absorption in the ultraviolet region, CO shows significant absorption in the infrared region, particularly around 4.3 and 15 microns, and HO has a complex absorption spectrum with multiple peaks in the infrared region [62, 64]. The total atmosphere absorption spectrum combines these effects, showing high absorption in the ultraviolet and infrared regions, with a notable "window" in the visible range where absorption is minimal [62, 64]. By comparing the two, it can be understood which wavelengths are most effectively absorbed by each gas and therefore limiting the transmission of energy back into space, ultimately contributing to the warming of the planet. This correlation is understood as follows:

Solar radiation emitted by the Sun is primarily composed of ultraviolet (UV) light, visible light, and infrared radiation (see Figure 2.7). When this radiation travels in the direction of Earth, it encounters the atmosphere, where 70 - 75 % of the radiation passes through (i.e., transmits) without being absorbed or scattered [62, 64]. The other 25 - 30 % of solar radiation emitted by the Sun gets reflected back into space by specific atmospheric gases like ozone, water vapor, and to a small extent also CO_2. Once the remaining solar radiation reaches Earth, it gets absorbed by oceans and landmasses, where it heats the Earth's surface and drives the planet's weather and climate systems [62, 64]. To maintain an equilibrium with the absorbed incoming energy, the Earth emits an equivalent amount of energy back into space. However, due to the Earth's lower temperature compared to the Sun, this energy is radiated at considerably longer wavelengths, i.e., in the infrared segment of the electromagnetic spectrum [65, 66]. This infrared radiation is emitted in all directions. Some of it escapes directly into space, which cools the Earth, while some is absorbed by atmospheric gases like water vapor, carbon dioxide, ozone, methane and nitrous oxide (see Figure 2.7). This additional warming is essential for life as we know it because it keeps the planet's average temperature at a hospitable level. Without the greenhouse effect, Earth's average surface temperature would be about -16 °C, rather than the current average of about 14 °C [67].

To understand why some molecules are categorized as greenhouse gases (i.e., absorb radiation) and others are not, it is essential to delve into the concept of molecular vibrations and dipole moments.

Understanding and Quantifying Major Greenhouse Gases

Molecules are not static; they exhibit various types of vibrational motions, including stretching, bending, and twisting of bonds [68, 69]. These vibrations change the distribution of electrons and the overall geometry of the molecule, which can lead to changes in the dipole moment - a measure of the separation of positive and negative charges within the molecule [68, 69].

A dipole moment occurs when there is a separation of charge within a molecule, leading to a positive end and a negative end [68, 69]. This separation can be permanent (as in polar molecules like water, where the oxygen and hydrogen atoms have different electronegativities) or transient (i.e., induced by molecular interactions or external fields). For a molecule to absorb radiation, the vibration or rotation must produce a change in the dipole moment of the molecule [68, 69]. This change allows the molecule to interact with the electric field component of the radiation, leading to absorption at specific wavelengths that correspond to the vibrational energies of the molecule [68, 69].

Molecules that are symmetrical often do not have a permanent dipole moment (see first row of lower-part in Figure 2.7) [69]. For example, homo-nuclear diatomic molecules like N2 or O2 do not have a permanent dipole moment because the electronegativity of the two atoms is the same, leading to an equal sharing of electrons [69]. Since there is no permanent dipole, and their symmetric vibrations do not induce a dipole change, these molecules do not absorb radiation [68, 69, 70].

Some of the major atmospheric molecules capable of absorbing radiation (i.e., greenhouse gases) are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halogenated gases, which include chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) [12, 13]. [2]

To uniformly assess the impacts of these greenhouse gases (GHGs) on climate change, emissions are measured in CO_2-equivalent units. This standard metric, known as Global Warming Potential (GWP), was developed by the Intergovernmental Panel on Climate Change (IPCC) [42]. It reflects how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2) (see equation 2.1) [13]. The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years [13, 14]. It is defined by a gases radiative efficiency (i.e., ability to absorb energy) and their lifetime (i.e., how long the gas stays in the atmosphere) [13].

$$GWP = \frac{\int_0^T a \cdot x(t)\, dt}{\int_0^T a_{CO2} \cdot x_{CO2}(t)\, dt} \tag{2.1}$$

Where T is the time horizon over which the GWP is calculated (e.g., 100 years), a is the radiative efficiency (in watts per square meter per kilogram) of the greenhouse

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[2] Ozone is also a greenhouse gas, but it mostly exists at much higher altitudes (i.e., 10 - 50 km above Earth's surface in the stratosphere) than other GHGs. While it does have a slight net warming effect on the planet, it absorbs harmful ultraviolet radiation from the sun and is considered beneficial to life on Earth. In the troposphere, however, ozone is an air pollutant and the main ingredient of urban smog [71]

gas, $x(t)$ is the decay function of the greenhouse gas over time t, a_{CO2} is the radiative efficiency of CO_2 and $x_{CO2}(t)$ is the decay function of CO_2 over time t.

The radiative efficiency, a , of a gas in the atmosphere, however, is not constant, but depends on the atmospheric concentration of the gas itself [72]. Therefore, the higher its atmospheric concentration the lower its radiative efficiency [72]. Therefore, changes in the concentration of the reference gas CO_2 have an impact on the GWPs of all other GHGs. This implies that GWPs are not constant over time and can only be calculated for given concentrations of GHGs. These natural fluctuations of GWPs over time, coupled with continuously advancing and updated scientific knowledge, account for the differences in GWP values given in various IPCC reports [72, 73, 74] as can be seen in Table 2.1

	IPCC 1992	IPCC 2005	IPCC 2021
Carbon dioxide (CO2)	1	1	1
Methane (CH4)	11	25	27.9
Nitrous Oxide (N2O)	270	289	273
Halogenated compound: CF4	-	7.390	7.380
Halogenated compound: SF6	-	22.800	24.300

TABLE 2.1: Global Warming Potentials (GWPs) for a 100-year time horizon for several greenhouse gases, as reported by the Intergovernmental Panel on Climate Change (IPCC) in different assessment reports from 1992, 2005, and 2021 [72, 73, 74]

Carbon dioxide (CO_2) is the most dominant anthropogenic greenhouse gas (GHG) in Earth's atmosphere[3], accounting for 76 % of all GHG emissions emitted from human activities in 2015 [75]. In 2023, global CO_2 emissions reached an all-time high with approximately 37.5 billion tonnes (Gt) being emitted, with an increasing trend noted for the following years [28]. Since industrialization, atmospheric CO_2 concentrations have increased by over +50 % from about 280 parts per million (ppm) to over 420 ppm in recent times [76, 77, 78]. The primary sources for this increase are the combustion of fossil fuels for generating electricity and heat, transportation, as well as industrial processes and deforestation [79]. CO_2, by definition, has a GWP of 1 regardless of the time period used, since it is the most prevalent GHG emitted by human activities, which makes it suitable as a reference gas, defined by the IPCC [72].

Methane (CH_4) has a concentration of 1.7 - 1.9 ppm in the Earth's atmosphere [80]. With a concentration increase of +162 % since pre-industrial times, it ranks as the fastest growing anthropogenic GHG released into the atmosphere [80, 81].

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[3] While water vapor is the most abundant greenhouse gas in the atmosphere (see Figure 2.7), human activities only have a small direct influence on its atmospheric concentration and it is therefore not included in this analysis. It is important to note, however, that human production of other greenhouse gases leads to an increase in atmospheric water vapor, due to warmer air being able to carry more water in its evaporated form. This creates a positive feedback loop, in which warming leads to more warming[71]

This is predominantly due to anaerobic processes in agriculture (e.g., decomposition of organic matter in manure, digestive process of cows, flooding of rice paddies, and irrigation practices in poorly drained soils); and from various stages in the fossil fuel production, processing, and distribution process. Since methane is often found alongside natural gas, oil, and coal deposits it can escape into the atmosphere through leaks in equipment and pipelines [82]. Methane is estimated to have a GWP of 27 - 30 over 100 years. It has a relatively short lifetime of approximately a decade on average, before it gets oxidized into CO_2 and water vapor [83]. This process is a significant sink for atmospheric methane and is much faster than the processes that remove CO_2 from the atmosphere, such as absorption by the oceans or incorporation into biomass through photosynthesis. Methane does, however, have a much higher radiative efficiency than CO_2, a characteristic attributed to its molecular composition that facilitates robust absorption within the infrared spectrum. This absorption band is less saturated than those associated with carbon dioxide, thus rendering methane a more formidable greenhouse gas on a per-molecule basis [83]. The net effect of the shorter lifetime and higher energy absorption is reflected in its GWP [13].

Nitrous oxide (N_2O) is another significant greenhouse gas, with a concentration of 0.336 ppm in the Earth's atmosphere and an increase of 24% since pre-industrial times [84]. It is emitted through agricultural activities, such as the use of nitrogen-based fertilizers, the decomposition of crop residue, and the management of manure; as well as during combustion of fossil fuels and biomass [84]. N_2O has a GWP 198 - 265 times that of CO_2 for a 100-year timescale [72, 73, 74]. Its lifetime accounts for an average of 114 years, and it is over 250 times more effective at trapping heat in the atmosphere than CO_2 [13]. Although N_2O is present in much lower concentrations in the atmosphere than CO_2, its higher GWP means that its contribution to the greenhouse effect is disproportionately large relative to its concentration [85].

Halogenated gases (CFCs, HFCs, HCFCs, PFCs, and SF_6) are typically emitted in smaller quantities than other greenhouse gases and make up a concentration of 1 - 1000 parts per trillion (ppt, i.e., 0.00001 - 0.01 ppm) in the Earth's atmosphere [71]. They are, however, the most potent greenhouse gases with GWPs that typically range from thousands to tens of thousands [82]. SF_6, for example, is used in the electrical industry and has a GWP of 23.500 over 100 years [13]. The concentrations of these gases were essentially zero a few decades ago, but have rapidly increased as they have been incorporated into industrial products and processes (e.g., refrigerants, foam-blowing agents for insulation and packaging, solvents for industrial processes, fire suppressants, and semiconductor manufacturing) [13]. Some of these chemicals have been or are currently being phased out (e.g., CFCs in refrigeration/air conditioning and SF_6 for electrical equipment), due to their ozone-depleting tendencies, which explains the big range of +10 - 80 % increase since pre-industrial times.

Understanding the GWP of different gases and their contribution to the greenhouse effect is crucial for developing strategies to mitigate climate change. The quantification of a gases climate impact provides a common unit measure, which allows analysts to add up emission estimates of different gases and allows policy-makers to compare emission reduction opportunities across sectors and gases [13]. How the EU's policy framework for transitioning from fossil fuels to alternative energy sources has evolved and is currently structured, is explained in the following.

2.4 EU's Policy Frameworks to Transition from Fossil Fuels to Alternative Energy Sources

The EU is actively pursuing the substitution of fossil fuels with low-emitting, alternative fuels through a variety of strategies and initiatives. Some key policy frameworks and their development can be seen in Table 2.2.

EU Recommendations Concerning the Promotion of Alternative Fuels	
TYPE OF RECOMMENDATION	**DESCRIPTION**
Kyoto Protocoll (1997 - 2005)	International treaty setting targets for industrialised countries to reduce greenhouse gas (GHG) emissions
Biofuels Directive (2003/30/EC)	Promotion of biofuels within the EU's transportation sector
EU Emissions Trading System (ETS, 2005)	Market-based approach to limit CO2 emissions from certain industries by allocating or selling emission allowances
Renewable Energy Directive (2009)	Binding targets for EU member states to increase share of renewable energy in the energy mix by 20 % by 2020
Paris Agreement (2015)	Global treaty with the committment of combating climate change
European Strategy for Low-Emission Mobility (2016)	Shift towards low-emission and zero-emission vehicles to reduce CO2 emissions from the transport sector
EU Renewable Energy Directive II (2018)	More ambitious renewable energy targets of at least 32 % by 2030
European Green Deal (2019)	Goal: Climate neutrality by 2050

TABLE 2.2: EU Recommendations and Policies Concerning the Promotion of Alternative Fuels

The Kyoto protocol laid the foundation for global cooperation on emissions reduction and extended the 1992 United Nations Framework Convention on Climate Change (UNFCCC), committing its parties to reduce greenhouse gas emissions by 8 % below 1990 levels by 2012 [86]. This commitment shaped EU energy policies, particularly in promoting the reduction of fossil fuel use and enhancing the role of renewable energy sources. However, the Protocol lacked enforceability and substantial participation, necessitating the development of stronger mechanisms.

In 2003, the Biofuels Directive (2003/30/EC) was released, aiming at promoting the use of biofuels within the EU's transportation sector [87]. This directive set indicative targets for Member States to increase the market share of biofuels in gasoline and diesel for transport purposes of 2 % by the end of 2005 and 5.75 % by the end of 2010 [88].

In 2005, the EU Emissions Trading System was formulated to introduce a market-driven approach, encouraging emission reductions through trading and incentives participation [89]. This system is especially important for the sectors of power generation, energy-intensive, and aviation.

In 2009, the first Renewable Energy Directive (RED) set a mandatory national target of 20 % renewable energy consumption by 2020, including a sub-target of 10 % biofuels in the transport sector [90]. This directive reinforced the use of biofuels and other renewable energy sources, which had already been promoted six years prior, in the Biofuels Directive (2003/30/EC) [87].

In 2015, the Paris Agreement was signed, marking a significant global commitment to climate action [91]. Although not an EU-specific policy, the European Union ratified this agreement, which catalyzed a series of intensified efforts within the EU to reduce reliance on fossil fuels. This led to the revision of existing directives and the setting of new, more ambitious environmental targets [92].

Following the ratification of the Paris Agreement, the European Union unveiled the European Strategy for Low-Emission Mobility (ESLEM) in 2016 [93]. This strategy was designed to achieve a substantial reduction in transport emissions by 2050, positioning alternative fuels as a pivotal bridge technology. ESLEM specifically aimed to address the urgent need to cut transport emissions more aggressively and promoted the use of E-fuels as a transitional solution.

Another significant development influenced by the Paris Agreement was the revision of the Renewable Energy Directive (RED) to RED II in 2018 [94]. RED II set a more ambitious target for the EU, aiming for 32 % renewable energy by 2030. This included a specific goal of achieving a 14 % share of renewable energy in the transport sector, thereby encouraging the use of biofuels and E-fuels.

While RED II primarily focuses on increasing the share of renewable energy in the EU's overall energy mix, ESLEM targets the reduction of emissions from the transport sector. It emphasizes the transition towards low-emission and zero-emission vehicles, aligning with the broader objectives of the Paris Agreement to mitigate climate change through sustainable energy and transportation policies.

In 2019, the European Commission introduced the European Green Deal, a comprehensive plan designed to achieve climate neutrality in Europe by 2050 [95]. This ambitious initiative focuses on reducing emissions, investing in green technologies, and safeguarding the natural environment, all while ensuring that economic growth is not dependent on increased resource use. The Deal includes several key strategies, central to which is the energy transition outlined in the EU's 'Fit for 55' package. This package sets a target to cut net greenhouse gas emissions by at least 55% by 2030, relative to 1990 levels. Additionally, the Green Deal emphasizes significant improvements in energy efficiency, particularly in building infrastructures. It also advocates for a shift in transportation methods, including a greater reliance on electric vehicles, hydrogen fuel cells, and the expansion of sustainable biofuels. Furthermore, it promotes the use of sustainable fuels in aviation and maritime transport. Overall, these strategies are part of a broader effort to phase out fossil fuels and tackle climate change effectively.

Recent developments and future plans for mitigating climate change and ensuring energy security still focus heavily on the phasing out of finite fossil fuels. Ahead of COP28, the EU announced plans to push for a global pledge to phase out unabated fossil fuels well ahead of 2050. This includes tripling the roll-out of renewable energy by 2030 and improving energy efficiency [96]. Additionally, the EU has enacted policies to end the use of fossil fuel-powered boilers and limit the installation of new fossil-based heating systems, a move that is integral to the EU's strategy to reduce carbon emissions from residential heating [97].

Furthermore, the EU is taking steps to deter new investments in fossil fuel infrastructure by introducing financial regulations. These regulations stipulate that any financial investments in fossil fuels must be fully supported by the investing institution's own capital, acknowledging the high financial risk associated with such investments [98].

As the implementation of diverse policies and strategies aimed at transitioning away from fossil fuels continues, it is essential to develop a comprehensive understanding of the various alternative fuel options available. This knowledge is crucial for determining the most suitable alternatives for specific applications, thereby effectively mitigating climate change and enhancing energy security. A detailed examination of these alternatives will be presented, as well as the methodology used to obtain these results.

Chapter 3

Methods

3.1 Data Sources

The methodology encompasses a comprehensive approach to data collection to ensure that the gathered information is robust, relevant, and up-to-date. The primary data sources chosen for understanding alternative fuels include scientific literature, industry reports, and government publications. Each source provides unique insights that collectively contribute to a holistic understanding of the potential of alternative fuels—specifically hydrogen, biofuels, and synthetic fuels—as replacements for fossil fuels. The scientific literature cited, encompasses peer-reviewed journals, conference papers, and academic books that delve into the production processes, availability, cost-efficiency, political support, and technological readiness of alternative fuels. This body of work provides a theoretical foundation and empirical evidence essential for grasping the current state and future potential of these fuels. It is used for hypothetical calculation models to highlight specific challenges associated with biofuel production and synthetic fuel utilization. Industry reports, produced by energy companies, market analysis firms, and industry associations, offer practical insights into market dynamics, technological advancements, and the economic viability of alternative fuels. These reports often feature data on production costs, market trends, and case studies, which are crucial for evaluating the real-world applicability of alternative fuels, such as the case study on Rail Cargo Group reach stackers in four European locations. Government publications, including policy documents, regulatory frameworks, and environmental impact assessments from relevant agencies, provide information on the political and regulatory landscape. These documents help in understanding the level of political support and regulatory requirements that could influence the adoption of alternative fuels. These types of documents are often used to provide an outlook into the future utilization of hydrogen, biofuels, or synthetic fuels as alternative fuels, respectively.

For data to be considered, it must directly relate to the research objectives defined in the Introduction, and focus on the production processes, availability, cost-efficiency, political support, and technological readiness of hydrogen, biofuels, and synthetic fuels. This ensures that the data is pertinent to the core questions of the master's thesis. Preference is given to recent publications (within the last 10 years) to ensure that the information is current and reflects the latest developments in the field. Seminal works that have laid the foundation for current research are also included to provide historical context and a comprehensive understanding of the topic.

3.2 Environmental Impact Assessment

The quantitative analysis is based on statistical techniques either obtained from scientific literature, or utilized in simple calculation models to highlight the environmental impact of specific challenges associated with biofuel and synthetic fuel production, respectively. These techniques are utilized to summarize data on production costs, availability, and environmental impacts of alternative fuels. This includes calculating measures of central tendency (mean, median) and dispersion (standard deviation, range) to provide a clear and concise overview of the data. Inferential statistics, such as regression analyses, are employed to identify simple trends and correlations, thereby elucidating the relationships between different variables. Approximations of Life Cycle Analyses (LCA) are implemented to assess the environmental impacts of each fuel type. These models consider the entire lifecycle of the fuels, from production to end-use, focusing on greenhouse gas emissions, energy consumption, and resource use. Cost-Benefit Analyses (CBA) are used to evaluate the economic viability of integrating alternative fuels by comparing the total costs (production, infrastructure, maintenance) with the benefits (reduced emissions, fuel savings).

Before calculations are performed, the assumptions made are described beforehand. However, when it comes to energy statistics there are several assumptions and calculation methods that need to be explained in detail:

3.2.1 Energy Statistics Conventions and Reporting

Concerning energy statistics, a set of conventions is adhered to for consistency and clarity in reporting and analysis. These conventions are pivotal for understanding the domestic production of energy, the treatment of international trade, and the reporting requirements for countries. The key conventions include

- The classification of nuclear installations and the subsequent generation of electricity and heat as domestic production, irrespective of the uranium or plutonium's origin. Similarly, biofuels produced from imported biomass feedstock are considered domestic biofuel production, disregarding the biomass feedstock's actual origin.

- The assessment of imports and exports is based on the physical crossing of borders, independent of customs procedures. Countries are mandated to report the ultimate origin of fuels for imports, specifically the country where the fuel was extracted, while generally excluding transit from reporting.

- The consumption of fossil fuels encompasses not only energy consumption but also non-energy uses. This includes the utilization of fossil fuels in the chemical industry, construction, and all other industries.
- For the European Union, the aggregate data is the sum of individual country data. Consequently, for trade, this aggregate includes intra-EU trade, providing a comprehensive overview of the EU's energy landscape.

Concerning the reporting of trade (imports and exports) in energy statistics, there are several considerations to be aware of:

- Some countries classify transit as imports and exports, which can lead to an overestimation or misrepresentation of a country's actual energy trade flows, as transit trade is not intended for domestic consumption or production. It is therefore paid special attention to a clear distinction.
- Certain data, such as Austria's reporting on natural gas trade, are considered confidential and are not disclosed in detail. This lack of transparency can lead to potential inaccuracies in estimating energy trade flows due to the absence of actual data. However, robust estimation methodologies have been established and clearly documented before any such calculation
- Most of the energy data available pertains solely to Europe. Since the analysis has a political perspective, arguments are given in the context of the European Union. Therefore, the energy data of Europe is modified by subtracting export and import figures from Norway and the UK. This approximation is deemed acceptable for illustrating the EU27's dependency on external energy sources. It can, however, lead to an underestimation or overestimation of the actual energy trade balance, depending on the magnitude of trade with Norway and the UK. This method of approximation is still deemed suitable for answering the main proposal questions, which are more environmentally motivated, than trade-oriented.

The qualitative analysis is based on framework analysis and a case study approach. Thematic analyses are applied to qualitative data from policy documents and industry reports to identify key themes related to political support and technological readiness. This involves coding the data to identify patterns and themes that provide insights into the factors supporting or hindering the adoption of alternative fuels.

A detailed investigation of RCG reach stackers at four European locations is conducted to gain practical insights. This includes interviews with stakeholders and the analysis of operational data provided by technical data sheets. The case study approach allows for an in-depth understanding of the real-world application of alternative fuels in specific contexts.

3.3 The Overall Evaluation of Suitable Alternative Fuels

The evaluation of alternative fuels is based on their environmental impacts, economic viability, technological readiness, and political and regulatory support. The results are summarized and discussed to provide recommendations for future research and practical application. The findings provide a foundation for future research in the field of alternative fuels. Several areas for further investigation are identified, including broader applications, long-term studies, and technological innovations.

Chapter 4

Types of Alternative Fuels

4.1 Overview of Alternative Fuel Categories

The imperative need for alternative fuels arises from the finite nature of fossil fuel reserves, challenges in energy security, and significant environmental impacts, as detailed in chapter 2. Consequently, alternative fuels are being increasingly explored as viable substitutes for fossil fuels. These domestically produced fuels can reduce dependence on imported oil and are emerging as a crucial component in society's efforts to decarbonize and limit global warming [99, 100]. However, the definition and understanding of the term 'alternative fuels' vary among scientist and politicians, leading to confusion in the industry, particularly in differentiating sustainable alternatives to conventional fuels [101]. Generally, alternative fuels refer to any fuel other than gasoline or diesel that is used to power vehicles, engines, or other fuel-consuming equipment, partly or wholly derived from sources other than naturally occurring fossil fuel sources [102].

The current Alternative Fuel Initiative (AFI) Directive recognizes seven types of alternative fuels [103]: electricity, hydrogen, synthetic fuels, biofuels, compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LPG).

These alternative fuels have a variety of advantages to fossil fuels, such as providing multiplicity of fuel sources and loosening dependence on fuel-exporting countries, as well as partially improving fuel densities. They do, however, *not* guarantee a (significant) reduction of carbon emissions. To identify and differentiate fuels based on their environmental impact, 'low-emission alternative fuels' have been defined by various organizations and regulatory bodies, like the International Energy Agency (IEA). These types of fuels can be produced from biomass, or through industrial processes powered by renewable energy sources or other low-emission energy sources. While CNG, LNG, and LPG are often considered cleaner alternatives to traditional fossil fuels, they are not categorized as low-emission alternatives by the IEA [104] and will therefore be excluded from further investigation.

Additionally, while there is a global effort in electrifying as many technologies as possible, for some applications batteries may be unsuitable due to several effects: i) the energy density may be too low if the vehicle needs to be lightweight (e.g., aviation); ii) a high degree of autonomy needs to be achieved (e.g., long-duration robotic missions); and iii) a very short refueling time is essential (e.g., commercial vehicles).

Therefore, the focus of this research is on alternative fuels that are considered low-emitting and non-electric. The remaining types of alternative fuels (i.e., hydrogen, synthetic fuels, and biofuels) will be discussed in great detail in the following sections.

4.2 Hydrogen as an Alternative Fuel

4.2.1 Overview and General Properties of Hydrogen

Hydrogen as an alternative fuel is a topic of significant scientific and technological interest, due to its potential to provide an abundant, clean, and secure renewable energy source [105, 106].

The Physical Properties of Hydrogen

are characterized by being a colorless, odorless, and tasteless gas at standard temperature and pressure, distinguished by having the lowest density of all gases. This characteristic poses significant challenges for its storage and transport, as hydrogen requires high-pressure tanks or must be maintained at cryogenic temperatures to be efficiently stored as a liquid or compressed gas [107]. In terms of energy density, hydrogen possesses a high energy content by weight, approximately 120 - 142 MJ/kg, which is nearly three times higher than that of petroleum fuels (i.e., 44 and 48 MJ/kg for gasoline and diesel, respectively) [107], making it valuable for applications where weight is a critical factor. However, its energy density by volume is around 6 times lower compared to petroleum fuels under ambient conditions, indicating a larger storage volume for one unit of energy [108]. This necessitates the compression or liquefaction of hydrogen for its practical use in vehicles, ensuring it can be utilized effectively as a fuel source. Hydrogen's high diffusivity and low viscosity mean that it can easily leak through materials, more so than other fuels. This characteristic demands the use of special materials and technologies designed to safely handle and contain hydrogen, preventing leaks and ensuring safety in its applications.

The Chemical Properties of Hydrogen

offer significant environmental benefits when it comes to combustion and emissions. Upon combustion, hydrogen reacts with oxygen to produce primarily water vapor, resulting in no direct emissions of pollutants or other greenhouse gases. However, at high combustion temperatures, nitrogen oxides (NOx) may still be produced due to the reaction between nitrogen and oxygen in the air, which is a consideration in its environmental impact [107, 109]. Hydrogen also features a wide flammability range, from 4 % to 75 % in air, and can ignite with very low energy input—about a tenth of that required for gasoline. This makes hydrogen both highly efficient and potentially hazardous, with a high flame speed and low ignition energy contributing to its profile as a fuel that must be handled with care [107, 110]. Furthermore, hydrogen plays a crucial role in fuel cells, where it acts as a reactant. In these applications, hydrogen generates electricity through electrochemical reactions rather than combustion. This process involves the movement of hydrogen protons through a membrane, where they react with oxygen to produce water, electricity, and heat, showcasing hydrogen's versatility and potential as a clean energy carrier [111].

4.2.2 Production Methods of Hydrogen Fuel

Hydrogen is the most abundant element in the universe, but it is not present in great quantities on Earth [105]. It is commonly locked up in enormous amounts of water, hydrocarbons, and other organic matter and must be freed through various production methods [112]. However, it is crucial to note that not all hydrogen production methods are environmentally benign. While hydrogen fuel itself does not emit carbon dioxide upon combustion, the current methods of hydrogen production, storage, and transport have other environmental implications. To more effectively differentiate between the various hydrogen production methods, they are categorized within a 'Hydrogen Color Spectrum', visualized in Table 4.1.

	Method of hydrogen production (i.e., the process)	**Resources consumed to produce the required energy**	**Economic costs**	**CO_2 equivalent emissions (in kg) per 1 kg hydrogen production**[113]
Green Hydrogen	Electrolysis	Renewable Energy	$$$	approx. 0.5
Pink Hydrogen	Electrolysis	Nuclear Energy	$$$	0.1 - 0.3
Blue Hydrogen	Steam Reforming with Carbon Capture	Natural Gas	$$	0.7
Gray Hydrogen	Steam Reforming	Natural Gas	$	approx. 9
Turquoise Hydrogen	Pyrolysis	Methane	$$	approx. 0.5
Brown/Black Hydrogen	Gasification	Coal	$	22 - 26

TABLE 4.1: Hydrogen is categorized in the 'Hydrogen Color Spectrum', depending on various categories.

From an environmental perspective, brown/black hydrogen produced through coal gasification is the most detrimental, with CO_2 emissions ranging from 22 to 26 kg CO_2-eq per kg of hydrogen. In 2020, approximately 20 % of hydrogen production was attributed to brown/black hydrogen [113].

Hydrogen production from natural gas without carbon capture and storage (CCS), known as gray hydrogen, results in direct emissions of around 9 kg CO_2-eq per kg of hydrogen. In 2020, gray hydrogen accounted for about 60 % of global hydrogen production, making it the most prevalent form [113]. By implementing CCS technologies at steam reforming hydrogen plants, the direct emissions can be significantly reduced to approximately 0.7 kg CO_2-eq per kg of hydrogen, resulting in what is termed blue hydrogen [113].

The emissions from hydrogen production via water electrolysis depend on the emissions associated with electricity generation and transport. In countries like Sweden, which boasts one of the lowest emission factors for grid electricity production globally, the emission intensity can be as low as 0.5 kg CO_2-eq per kg of hydrogen [113].

Nuclear electricity is another potential source for hydrogen production. While the direct emissions from a nuclear plant are zero, the entire nuclear fuel cycle - including uranium mining, conversion, enrichment, and fuel fabrication - results in emissions ranging from 0.1 to 0.3 kg CO_2-eq per kg of hydrogen [113]. This incredibly low value is due to the technique producing solid carbon instead of CO_2.

4.2.3 Low-Emitting Hydrogen Production Methods

For hydrogen to be qualified as low-carbon in the EU, the emissions of the production life-cycle must be lower than 3.38 kg CO_2-eq/kg H2 [114]. The subsequent analysis will focus exclusively on low-emitting and sustainable types of hydrogen that meet this criterion, including green hydrogen produced via electrolysis of water using renewable electricity; pink hydrogen, also produced via electrolysis of water using nuclear energy; blue hydrogen produced from natural gas via steam methane reforming coupled with carbon capture and storage (CCS) technology; and turquoise hydrogen produced by pyrolysis of natural gas into hydrogen and solid carbon. Each of these types of hydrogen will be discussed in detail in the following sections. In contrast, brown/black and gray hydrogen, despite currently dominating production, will not be further discussed due to their higher emission profiles.

Production and Potential of Green and Pink Hydrogen

Green and pink hydrogen are produced via electrolysis of water and differ in the type of energy used to power the process (see Figure 4.1). While green hydrogen uses electricity from renewable wind, photovoltaic (PV), or hydro-energy, pink hydrogen is made with nuclear energy. Both processes are characterized by their low

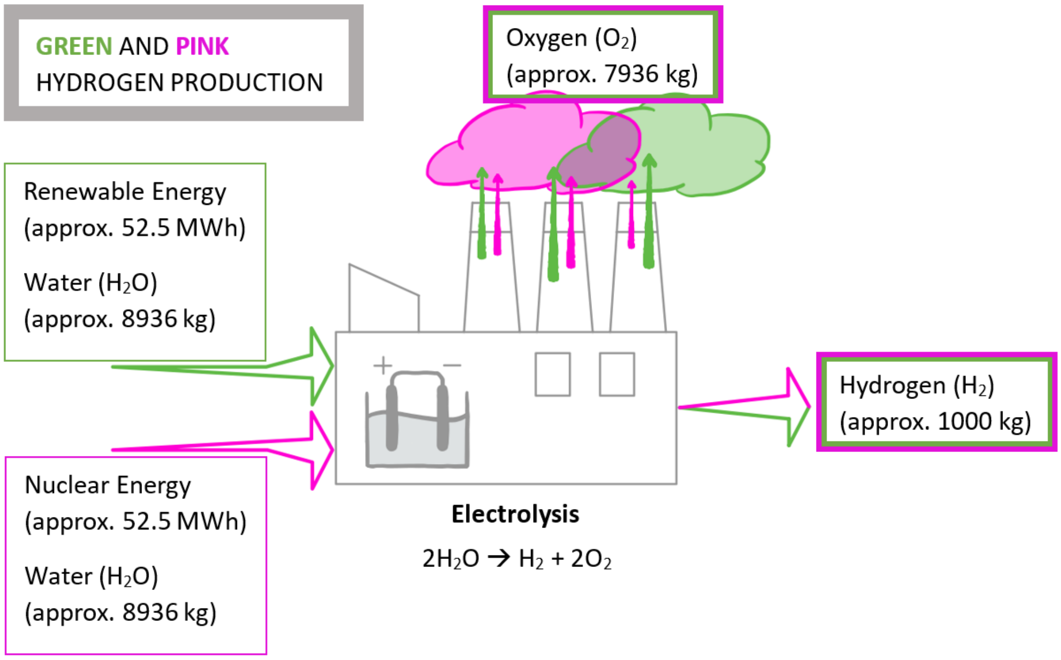

FIGURE 4.1: The production process of green and pink hydrogen utilizes renewable and nuclear energy sources to produce hydrogen via electrolysis, respectively. Information used to construct this Figure was sourced from [115, 116]

carbon emissions (see Table 4.1) and high operational costs compared to other production methods.

The production process is characterized by electrolysis, which involves the passing of an electric current through water in an electrolyzer, that breaks the water molecules into hydrogen and oxygen gases, following the reaction equation depicted in Figure 4.1. The hydrogen gas is then captured and stored, while the oxygen is released into the atmosphere or used for other industrial purposes. To produce 1000 kg of green or pink hydrogen, approximately 8936 kg of water and 52.5 MWh of renewable or nuclear energy are needed, respectively [115].

The main technology lies in the type of electrolyzer used. There are multiple types of electrolyzers available, each with distinct characteristics, efficiencies, and associated costs, offering various options for hydrogen production depending on the specific requirements and resources of the operation.

Alkaline Electrolyzers are one of the most mature and widely used technologies for hydrogen production. They operate by using an alkaline solution of potassium or sodium hydroxide as the electrolyte. Water reacts at the anode to produce oxygen and positively charged hydrogen ions (protons). These protons move through the electrolyte to the cathode, where they are reduced to hydrogen gas. Alkaline electrolyzers are known for their reliability and relatively low cost but have limitations in terms of efficiency and operational flexibility [117, 118, 119].

Proton Exchange Membrane (PEM) Electrolyzers use a solid polymer electrolyte and operate at higher efficiencies compared to alkaline electrolyzers. They can start and stop rapidly, making them ideal for pairing with intermittent renewable energy sources like wind and solar power. The PEM electrolyzer's ability to operate at higher pressures reduces the need for external compression of hydrogen, potentially lowering storage costs. However, the use of expensive catalysts such as platinum and iridium increases the cost of PEM electrolyzers [120, 121].

Solid Oxide Electrolyzer Cells (SOECs) operate at high temperatures (typically between 500 °C and 850 °C) and use a ceramic material as the electrolyte. The high operating temperature allows for higher efficiency due to the improved thermodynamics of the water-splitting reaction. SOECs can also integrate with heat sources, such as nuclear reactors in the case of pink hydrogen, to further enhance efficiency. However, the high temperature leads to challenges in terms of material stability and longevity, which can add to the costs [116, 122].

Despite the strides made in technological advancements, the production costs of green and pink hydrogen remain higher compared to traditional methods such as gray and brown/black hydrogen production, due to initial capital and energy costs. However, focusing solely on cost comparisons overlooks the broader benefits and potential of these sustainable hydrogen sources.

Green hydrogen, for example, is particularly advantageous in remote and arid areas where maintenance needs are minimal and the direct generation of electricity from renewable sources can be efficiently utilized [123]. This method can also serve for grid stabilization by leveraging excess electricity and therefore aiding the balance in supply and demand, while producing low-emission hydrogen [124, 125, 126].

Examples of initiatives focusing on green hydrogen production include 'H2 Energy Europe's' plan to build one of Europe's largest facilities for green hydrogen production in Esbjerg, Denmark, aiming to utilize renewable energy sources for hydrogen production. Similarly, 'Everfuel' is focused on commercializing green hydrogen for transportation in Scandinavia, emphasizing the production and distribution of hydrogen made from renewable sources.

Pink hydrogen offers a stable and reliable alternative for hydrogen production in regions with established nuclear power infrastructure. It leverages the continuous and high-output nature of nuclear energy, making it a viable option for large-scale hydrogen production. However, it is important to note that although nuclear energy has been labeled a sustainable energy source by the EU, it still requires uranium, which is a finite resource and often comes from regions outside the EU, raising potential supply chain and geopolitical concerns. This dependency on external sources could pose risks to the stability and sustainability of pink hydrogen production [127].

Production and Potential of Blue Hydrogen

Blue hydrogen is produced through a process known as steam reforming or steam methane reforming (SMR), where natural gas is reacted with steam under high temperatures to produce hydrogen and carbon dioxide (CO_2) [128]. Unlike green and

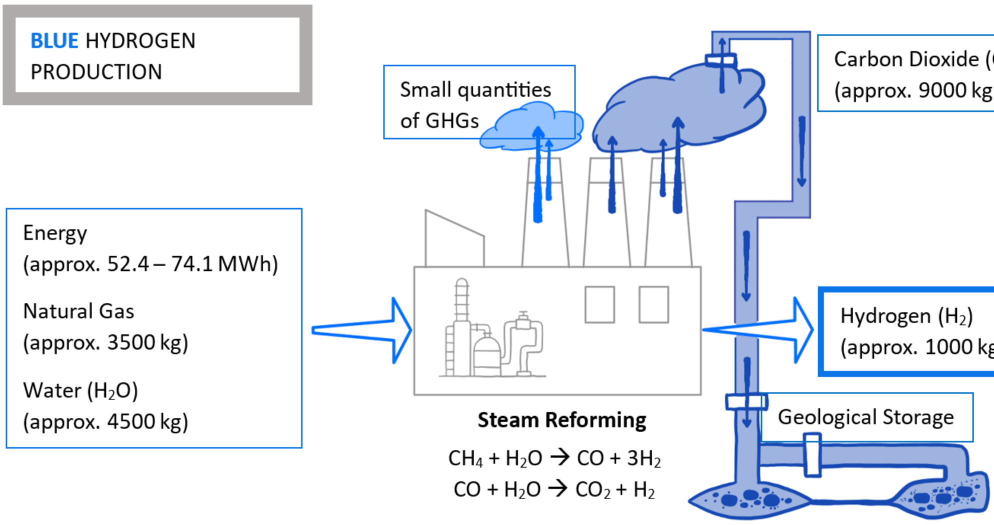

FIGURE 4.2: The production process of blue hydrogen involves steam reforming of natural gas combined with carbon capture and storage (CCS) Information used to construct this Figure was sourced from [128, 129, 130]

pink hydrogen, which utilize electrolysis powered by renewable and nuclear energy respectively, blue hydrogen uses fossil fuels as its primary energy source but captures and stores the emitted CO_2, giving this production method the potential of being carbon neutral, as depicted in Figure 4.2 [129, 130]. The carbon capture and storage (CCS) technology is key in turning the previous gray hydrogen 'blue', as it is essential for reducing the carbon footprint of this method (see Table 4.1).

The steam reforming process involves mixing methane (CH_4), the primary component of natural gas, with steam at a temperature of around 700 °C to 1,000 °C [128]. This reaction occurs in the presence of a catalyst, typically nickel-based, which facilitates the conversion of methane and water into hydrogen and carbon dioxide. The reaction equation for this process can be seen in Figure 4.2.

Following the production of hydrogen, the CO_2 generated is captured using various technologies such as amine scrubbing, membrane separation, or pressure swing adsorption. The captured CO_2 is then transported and stored underground in geological formations [131]. By adding CCS technology to existing gray hydrogen steam reforming facilities, blue hydrogen has the potential to become the most common method for hydrogen production globally [130]. However, the addition of CCS adds complexity and high costs to the hydrogen production process. It is, however, still less expensive to produce than green or pink hydrogen due to the lower cost of natural gas compared to electricity from renewable sources or nuclear power.

Challenges concerning long-term sustainability and environmental impact of blue hydrogen depend heavily on the effectiveness of the CCS employed [129, 130]. Current CCS technologies can capture around 85 - 95 % of emissions from this process, which are then permanently stored in geological formations like depleted oil/gas reservoirs or deep saline aquifers. However, there are risks of leakage from these storage sites over decades and centuries that could release the stored CO_2 back into the atmosphere, which must be considered in the environmental assessment of blue

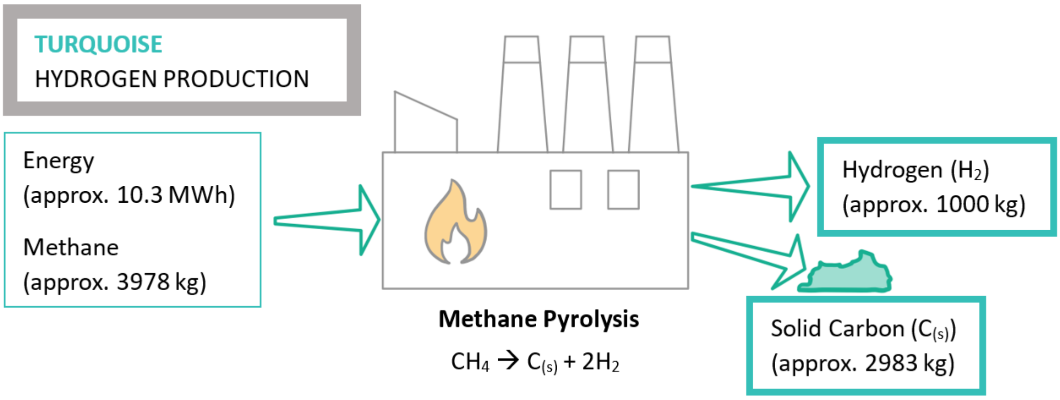

FIGURE 4.3: The production process of turquoise hydrogen involves methane pyrolysis to produce hydrogen and solid carbon. Information used to construct this Figure was sourced from [135, 136, 137, 138]

hydrogen.

To produce 1000 kg of blue hydrogen, approximately 3500 kg of natural gas and 4500 kg of water are required. The energy consumption is largely dependent on the efficiency of the steam reforming plant and the CCS technology employed, ranging between 52.4 - 74.1 MWh [132, 133, 134]. The carbon capture rate for blue hydrogen production typically ranges from 60 % to 90 %, significantly reducing the carbon emissions compared to traditional hydrogen production methods like gray hydrogen [130]. Although blue hydrogen does not reduce emissions to the same extent as green or pink hydrogen, it offers a robust and well-established method for producing hydrogen at scale.

Blue hydrogen is particularly advantageous in regions with abundant natural gas resources and where CCS infrastructure can be economically implemented, for example on top of gray hydrogen production facilities [130].

Production and Potential of Turquoise Hydrogen

Turquoise hydrogen is produced through a process known as methane pyrolysis, where methane (CH_4), the primary component of natural gas, is decomposed into hydrogen and solid carbon under high temperatures, typically in the absence of oxygen [135]. Unlike blue hydrogen, which relies on carbon capture and storage (CCS) to mitigate CO_2 emissions, turquoise hydrogen production results in solid carbon that can be used in various industries, such as manufacturing and construction, thereby potentially offering a more environmentally friendly alternative (see Figure 4.3) [135, 136].

The methane pyrolysis process involves heating methane at temperatures ranging from 1200 °C to 1600 °C in the presence of a catalyst such as carbon and iron ore or high-temperature plasma [137]. This high-temperature, anaerobic treatment causes the methane molecules to break down into hydrogen gas and solid carbon, without the formation of CO_2, as depicted in the reaction equation of Figure 4.3. This solid carbon, often referred to as carbon black, has significant commercial value and can be used in the production of tires, batteries, plastics, and even as a soil amendment [135, 136]. The ability to create a valuable byproduct, that not only prevents the emissions associated with gray hydrogen production but also circumvents the complexities and costs linked to capturing carbon in gaseous form as seen in blue hydrogen processes, makes turquoise hydrogen particularly appealing from an economic perspective [135].

To produce 1000 kg of turquoise hydrogen, approximately 3978 kg of methane and 10.3 MWh of energy are required [135, 138]. Unlike blue hydrogen, which has a variable carbon capture rate, turquoise hydrogen production results in no direct CO_2 emissions, although indirect emissions may occur depending on the energy source used for the process [135, 136]. Turquoise hydrogen is particularly advantageous in scenarios where the solid carbon byproduct can be effectively utilized, adding an economic incentive to its production. Moreover, in regions with access to renewable energy sources to power the pyrolysis process, turquoise hydrogen offers a promising route towards sustainable hydrogen production with minimal environmental impact [135, 136].

However, the technology behind turquoise hydrogen is still in its early stages of development. Scaling up to meet global hydrogen demand poses significant technological and logistical challenges, requiring substantial investment in research, development, and infrastructure [135, 136]. Especially, the practical and economical aspects of capturing, transporting, and utilizing this carbon at scale remain challenging.

4.2.4 Storage and Transportation of Hydrogen Fuel

After the production of green, pink, blue, or turquoise hydrogen through electrolysis, steam reforming, or pyrolysis, respectively, it is essential to transport it from the manufacturing site to the refueling stations. Because of its unique physical and chemical characteristics described in subchapter 4.2.1, hydrogen requires distinct storage and transportation methods that vary in cost-effectiveness, technological advancements and challenges, environmental advantages and drawbacks, and the level of policy backing. The subsequent discussion will explore these various storage and transportation approaches, considering the aforementioned factors.

Storage of Hydrogen Fuel

The storage of hydrogen occurs in either solid form (e.g., metal hydrides), gaseous form (e.g., compressed gas tanks), or liquid form at cryogenic temperatures or as ammonia [139, 140, 141].

Utilizing metal hydrides, like NaAlH4 to form reversible hydrogen bonds, stand out for their safety and stability, making them a promising hydrogen storage technology [139]. These materials can absorb hydrogen gas and release it when needed, offering a compact and relatively safe storage solution. This technology is unique in a sense, that it can store hydrogen under ambient conditions (i.e., at room-temperature and atmospheric pressure), which makes it beneficial for long-term and large-scale energy storage. Examples include mobile refuelers and backup power systems, that can be used in remote or emergency situations. However, they are not without their challenges. The slow reaction kinetics and the significant weight of the storage materials are considerable drawbacks [140, 142]. These limitations can affect fuel efficiency and practicality, especially for long-distance applications where weight and space are critical factors. The development of lighter materials with faster absorption and desorption rates could help overcome these challenges, but this requires ongoing research and technological advancements.

Compressed Hydrogen Gas Storage, which involves storing gaseous hydrogen in high-pressure tanks, is a relatively simple and efficient method for small to medium-scale applications. This storage method is applicable across a broad spectrum of industries, including automotive (e.g., hydrogen-powered vehicles) and aerospace (e.g., power source in rockets). The primary advantage of compressed hydrogen gas storage is its simplicity and efficiency, as it allows hydrogen to be used directly. However, the high pressures required (up to 700 bar) introduce several challenges, including the costs associated with tank construction and the energy needed for compression [139, 140]. There are also safety concerns related to the storage and handling of hydrogen at such high pressures. When considering energy storage, the volumetric energy density of compressed hydrogen is approximately 4.5 - 5.3 MJ/L, which is significantly lower than that of conventional fuels like gasoline and diesel, which stand at 32 MJ/L and 35 MJ/L, respectively (see Table 4.2). This lower density means that hydrogen storage solutions occupy more space for the same amount of energy, which can severely impact vehicle design and the efficiency of fuel transportation.

Liquid Form Storage requires hydrogen to be cooled down to cryogenic temperatures (-252.87 °C), which significantly increases the hydrogen density and ultimately the volumetric energy density to 70.8 kg H2/m3 and 8.49 MJ/L, respectively (see Table 4.2). This notable improvement over compressed gas storage is particularly advantageous for applications where space efficiency is critical, such as in aerospace. Additionally, for applications where the weight of the fuel is a critical factor, liquid hydrogen offers advantages due to its higher energy density by weight compared to many other fuels, including compressed hydrogen gas. However, maintaining such low temperatures necessitates great amounts of energy, as well as advanced insulation technologies to prevent boil-off losses, where stored liquid hydrogen turns into gas [140]. Common insulation materials include fiberglass paper and aluminum foil, but these are costly and contribute to the overall high expenses of cryogenic storage systems [139, 140]. Also, the transition from liquid to gaseous hydrogen not only decreases storage capacity but also poses serious safety risks, including explosion hazards, due to hydrogen's high flammability [107]. The lack of existing infrastructure for cryogenic hydrogen and the stringent safety measures required for handling and storage pose additional challenges. Additionally, refueling with cryogenic hydrogen can take longer than refueling with compressed gas, due to the need to carefully manage the transfer of cryogenically cold liquids. This can be a drawback for consumer vehicles or any application where rapid turnaround is desired.

Ammonia (NH3) can also be used as a liquid hydrogen storage, since this molecule can very effectively bind hydrogen, in the globally known Haber-Bosch process. Consequently, hydrogen can be stored and transported at much milder conditions (i.e., -33.34 °C) compared to cryogenic temperatures [143]. Among the various storage methods analyzed, ammonia has the highest hydrogen density by volume (= 108 kg H2/m3), which translates to a volumetric energy density of 12.7 MJ/L (see Table 4.2). This comparison, however, is not straightforward, since ammonia must first be converted back into hydrogen before it can be used as a fuel [140]. The conversion, known as cracking, necessitates catalysts to aid in the decomposition of ammonia and introduces additional complexity and energy costs. The energy penalty for this conversion ranges from 13 to 34 %, which diminishes the overall efficiency of energy storage and utilization [143]. Environmental aspects concern the toxicity of the liquid, as well as its potential of producing the potent greenhouse gas, nitrogen oxides (NOx), with a GWP of 273 (see Table 2.1), upon burning. In addition to its role as a hydrogen carrier, ammonia also serves as a significant chemical in agriculture and various industrial processes, enhancing its economic viability for transportation and storage. This intersection of ammonia between energy storage and vital fertilizer could, however, create competition for resources that could ultimately disadvantage global food production systems, where the agricultural sector may emerge as the unintended loser in the quest for cleaner energy solutions. A clear distinction of purpose is therefore needed to ensure no such competition arises.

In summary, while ammonia can be an effective carrier for hydrogen storage due to its higher volumetric hydrogen density compared to some forms of pure hydrogen storage, the necessity to convert ammonia back to hydrogen before use introduces additional steps, costs, and energy losses. It is still considered an attractive choice of hydrogen storage in scenarios where large-scale or long-distance energy transport is required.

Transportation of Hydrogen Fuel via Pipelines, Rail, Trucks, or Ships

The mode of transporting hydrogen - whether via pipelines, rail, trucks, or ships - depends on the state in which it is stored, such as solid in metal hydrides, gaseous in compressed gas storage, or liquid in cryogenic temperature storage or in the form of ammonia [144].

Hydrogen is transported via pipelines in regions with substantial demand that is expected to remain stable for decades. About 5,000 kilometers of hydrogen pipelines are already operational globally, primarily in the United States and Europe [144].

Hydrogen Storage Method	**Hydrogen Density by Volume** (in kg H2/m3)	**Volumetric Energy Density or Energy Content** (in MJ/L)	**Specific Energy** (in MJ/kg)
Metal Hydrides	-	-	-
Compressed Gas	23 (at 20 °C and 350 bar)	4.5 - 5.3	120 - 142
Cryogenic Hydrogen	70.8 (at -252.87 °C and atm. pressure)	8.49	120
Ammonia	108 (at 20 °C and 8.6 bar)	12.7	23
Fossil Fuel Comparison			
Gasoline	-	*32*	*44 - 47*
Diesel	-	*35*	*42 - 46*

TABLE 4.2: Comparison of Hydrogen Density and Energy Density of Various Storage Methods

These pipelines are rather small in diameter (about 18 inches) and are solely connecting onshore refineries and chemical complexes. A new hydrogen transmission system must be realized, to enable globalization of hydrogen transport. This can partly be achieved, by re-purposing parts of the already existing natural gas pipelines. Globally, there are approximately 1 million kilometers of natural gas transmission pipelines in operation, with an additional 69,700 kilometers under construction and over 220,000 kilometers in planning [145]. As the demand for natural gas decreases, re-purposing this infrastructure for hydrogen could help avoid the risk of stranded assets and reduce the average lead times for construction. These pipelines have diameters up to 48 inches and connect countries and/or continents. Such a hydrogen transmission system, while still in a rather futuristic stage, would differ significantly from existing local networks and more closely resemble current natural gas transmission, albeit on a smaller scale, due to the lower expected hydrogen consumption compared to today's natural gas consumption, even in the Net Zero Emissions (NZE) Scenario proposed by the International Energy Agency (IEA) [113]. The re-purposing of natural gas pipelines will make it the cheapest option for hydrogen transport up to a distance of 2.000 - 2.500 km.

For distances of more than 2.500 km, the transport of hydrogen is best facilitated by shipping using tanker ships, using ammonia as the carrier form of hydrogen as a option [113]. It does, however, require conversion and re-conversion facilities at either port, respectively. Approximately 150 terminal and ports are able to re-convert ammonia back to hydrogen, enabling global fuel trade on a theoretical basis. Current global ammonia trade, however, is around 20 Mt, equivalent to 3.5 Mt H2, which is well below the announced 12 Mt H2 by 2030 for ammonia-based projects [113]. Meeting this demand would require a tripling of existing ammonia trade infrastructure within this decade. While some capacity could be integrated into existing plants, potentially replacing fossil-based ammonia trading, or increasing annual plant utilization with minor adjustments, realizing the full potential of announced trade projects would require significant and currently unrealistic expansion [113].

Cryogenic liquid tanker trucks or gaseous tube trailers are two common modes of transporting hydrogen over roads for shorter distances compared to pipelines and shipping. Cryogenic liquid tanker trucks are equipped with heavily insulated tanks to maintain the intense conditions and minimize boil-off losses during the transportation of hydrogen [139, 140]. Due to the increased density of hydrogen under these conditions, the payload capacity compared to gaseous tube trailers is a lot higher. However, the liquefaction process itself is energy-intensive, and some hydrogen is lost during the liquefaction and boil-off processes [139, 140]. This form of transportation is suitable for transporting large quantities of hydrogen over moderate distances, typically up to a few hundred kilometers. They are commonly used to supply hydrogen to fueling stations or other end-users that require significant amounts of hydrogen. Gaseous tube trailers transport hydrogen in its compressed gaseous form, typically at pressures ranging from 200 to 500 bar (2,900 to 7,250 psi).

These trailers consist of multiple cylindrical tubes or vessels that are designed to withstand high pressures [146]. While gaseous tube trailers have a lower payload capacity compared to liquid tankers due to the lower density of gaseous hydrogen, they do not require the energy-intensive liquefaction process. Additionally, there are no boil-off losses associated with gaseous transportation [147]. Gaseous tube trailers are suitable for transporting smaller quantities of hydrogen over shorter distances, typically up to a few hundred kilometers. They are commonly used for supplying hydrogen to smaller fueling stations or industrial facilities with moderate hydrogen demands [147].

Both cryogenic liquid tanker trucks and gaseous tube trailers play crucial roles in the hydrogen supply chain, particularly for regional distribution and last-mile delivery. The choice between these two modes depends on factors such as the required quantity of hydrogen, distance, infrastructure availability, and economic considerations [147].

Intermodal transport involves the use of multiple modes of transportation, such as rail, road, and sea, to move hydrogen from production sites to end-users. This method leverages the strengths of each transport mode to optimize efficiency, cost, and environmental impact. Rail transport is a key component of intermodal hydrogen transport, particularly for long-distance and bulk shipments. Hydrogen can be transported in high-pressure cylinders or cryogenic liquid tanks on specialized rail cars. Rail transport offers high capacity and energy efficiency, making it suitable for moving large quantities of hydrogen over long distances. The infrastructure for rail transport is well-established in many regions, and existing rail networks can be adapted to handle hydrogen shipments with appropriate safety measures and equipment modifications. Road transport is often used for the initial and final legs of the intermodal journey, connecting production sites, rail terminals, and end-users. Hydrogen can be transported by cryogenic liquid tanker trucks or gaseous tube trailers, depending on the distance and quantity required. For international and intercontinental hydrogen transport, shipping by tanker ships is a viable option. Hydrogen is often transported in the form of ammonia or other hydrogen carriers, which are easier to handle and more stable for long sea voyages.

4.2.5 Comparative Assessment of Hydrogen Production, Storage, and Transportation Methods

From an environmental standpoint, green and pink hydrogen emerge as the most sustainable options due to their minimal carbon emissions. Green hydrogen is produced using renewable energy sources, while pink hydrogen is derived from nuclear energy, both resulting in negligible carbon emissions. However, the high costs associated with renewable energy infrastructure and nuclear technology make these options less economically viable compared to blue and turquoise hydrogen. Blue hydrogen offers a more cost-effective solution by utilizing natural gas with carbon capture and storage (CCS) technology. Nevertheless, its environmental impact is contingent on the effectiveness and long-term viability of CCS. If CCS technology fails to capture and store carbon efficiently, the environmental benefits of blue hydrogen diminish significantly. Turquoise hydrogen, which involves methane pyrolysis, shows promise due to its potential to utilize the solid carbon byproduct. However, its scalability and economic feasibility remain uncertain as the technology is still in its early stages. Balancing economic and environmental factors reveals no definitive winner among the different types of hydrogen. The optimal choice will depend on specific regional resources, infrastructure, and priorities. Green and pink hydrogen are the most environmentally sustainable options, while blue and turquoise hydrogen may be more economically viable in the short to medium term, contingent on the effectiveness of CCS and the utilization of the solid carbon byproduct, respectively. Ultimately, a combination of these hydrogen production methods, coupled with ongoing research and development to enhance efficiency and reduce costs, will likely be necessary to meet the growing global demand for hydrogen while minimizing environmental impact. Hydrogen storage can be achieved through various methods, each with unique benefits and challenges. Metal hydrides offer safety and stability for long-term storage but are hindered by slow reaction kinetics and weight. Compressed gas is efficient for small to medium-scale applications but faces high costs and safety concerns due to high pressures. Liquid hydrogen increases density but requires significant energy for cooling and advanced insulation to prevent losses. Ammonia, with the highest volumetric hydrogen density, is effective for large-scale transport but involves additional conversion steps and environmental concerns, as well as fertilizer vs. fuel debates. Transportation methods include pipelines, tanker ships, cryogenic liquid tanker trucks, gaseous tube trailers, and intermodal transport. Pipelines are economical for large quantities but require new infrastructure for global transport. Tanker ships are cost-effective for long distances but necessitate conversion facilities. Cryogenic trucks offer higher payloads but are energy-intensive. Gaseous tube trailers have lower capacity but avoid liquefaction issues. Intermodal transport optimizes efficiency by combining rail, road, and sea. In conclusion, hydrogen storage and transportation involve complex technological, economic, and environmental considerations. Each method has specific advantages and challenges, and the choice depends on application requirements, including scale, distance, and cost. A multifaceted approach, integrating various production, storage, and transportation methods, along with continued innovation, will be essential to effectively harness hydrogen's potential as a clean energy source.

4.2.6 Current Applications and Future Predictions of Hydrogen Fuel

In 2019, Dr. Fatih Birol, the Executive Director of the International Energy Agency (IEA), described hydrogen fuel in the report 'The Future of Hydrogen' [148] as follows:

> *'Hydrogen is today enjoying unprecedented momentum. The world should not miss this unique chance to make hydrogen an important part of our clean and secure energy future.'*

This rising enthusiasm for hydrogen as an alternative fuel is not just a momentum, but it is increasingly recognized as a versatile and clean energy carrier in various sectors, including industry, transportation, energy storage, and power generation. In industrial applications, hydrogen is the backbone of ammonia production, which consumes about 55 % of the global hydrogen supply, primarily for fertilizers [149]. The petroleum refining sector is another major consumer, utilizing roughly 25% of hydrogen to produce cleaner fuels [149]. Additionally, hydrogen is critical in methanol production, accounting for around 16 % of its usage, and is also employed in steel production, in various processes of metalworking and electronics, although the exact consumption figures in this sector are not detailed [150]. The transportation sector is witnessing a growing adoption of hydrogen, especially in fuel cell electric vehicles (FCEVs). By mid-2021, over 40,000 FCEVs were operational worldwide, with significant numbers in Korea, the United States, China, and Japan [151]. This category includes 6,000 buses and more than 3,100 trucks. Moreover, hydrogen fuel cell trains have commenced operations, notably in Germany, while the shipping and aviation sectors are exploring hydrogen's potential, albeit in the nascent stages [148, 152]. The prevalent storage method for hydrogen in FCEVs involves compressed hydrogen gas systems, which require high pressures and large volumes, presenting additional challenges [139]. Hydrogen's role in energy storage and power generation is increasingly vital, offering a solution to the intermittency challenges of renewable energy sources like solar and wind [124].

Despite the growing demand, which reached 90 million tonnes in 2020, predominantly for refining and industrial applications, the current hydrogen production landscape is significantly reliant on fossil fuels. This results in nearly 900 million tonnes of CO_2 emissions annually. The high costs of low-carbon hydrogen production pathways like green and pink hydrogen make them less economically viable presently. The path forward, therefore, involves overcoming this significant environmental impact, as well as hurdles related to production efficiency and cost [106]. The International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) have both underscored the potential for substantial cost reductions through technological innovation. According to IEA projections, the cost of hydrogen from renewable sources could fall to USD 1.3 per kilogram by 2030, making it competitive with hydrogen produced from natural gas with carbon capture, utilization, and storage (CCUS) (see Table 4.1) [153]. IRENA's report also suggests, that achieving cost-competitive renewable hydrogen is feasible within the next decade, with prices potentially dropping below USD 2 per kilogram before 2030 [154].

To align with Net Zero Emissions (NZE) goals for 2030 and 2050, significant investments and policy measures are essential to bridge the cost gap between low-carbon hydrogen and its fossil-based counterparts (see Table 4.3). These measures include advancements in water electrolysis technology, necessitating substantial reductions in capital expenditure (CAPEX) and improvements in technology effectiveness. Specifically, the CAPEX needs to decrease from the current range of 1000 - 1750 USD/kWe to 400 - 440 USD/kWe by 2030, and further to 320 - 340 USD/kWe by 2050 (see Table 4.3). Additionally, improvements in the technology's effectiveness, measured as the lower heating value, need to improve from 64 % today, to 69 % in 2030, and 74 % in 2050. Operational expenditure (OPEX) is expected to remain constant at 1.5 - 3% of CAPEX, indicating no increase in operational costs relative to capital investment are likely to occur. Additionally, while the stack lifetime can reach up to 95.000 h, 50.000 h are chosen, based on the IEA's analysis of the optimum economic lifetime, considering degradation issues.

Parameter	**Units**	**Today**	**NZE 2030**	**NZE 2050**
CAPEX	USD/kWe	1000 - 1750	400 - 440	320 - 340
Efficiency (LHV)	%	64	69	74
Annual OPEX	% of CAPEX	1.5 - 3	1.5 - 3	1.5 - 3
Stack lifetime	operating hours	50.000	50.000	50.000

TABLE 4.3: Comparison of key hydrogen production parameters for CAPEX, Efficiency, Annual OPEX, and Stack lifetime from today to NZE 2030 and NZE 2050.

4.3 Biofuels as Alternative Fuels

4.3.1 Biofuel Generations and Production Pathways

Theoretically, every organic material has the potential to act as a biofuel. Practically, this potential is influenced by a variety of factors including economic considerations like the cost and availability of feedstock, market prices, and subsidies; environmental concerns such as sustainability, land use, and greenhouse gas emissions; technical and physical attributes like energy content, conversion efficiency, the physical and chemical properties of the feedstock; and the technological readiness of conversion technologies alongside ongoing research and development efforts [167, 168, 169]. A structured overview of renewable feedstocks that meet these criteria by EU standards are illustrated in the 'Eligible Biomass' column of Figure 4.4 [155]. These biomass types are categorized into three distinct generations, each defined by the nature of the feedstock and the specific processing methods applied. In the Figure 4.4, these generations are visually differentiated by color coding: first generation in blue, second generation in orange, and third generation in green. While

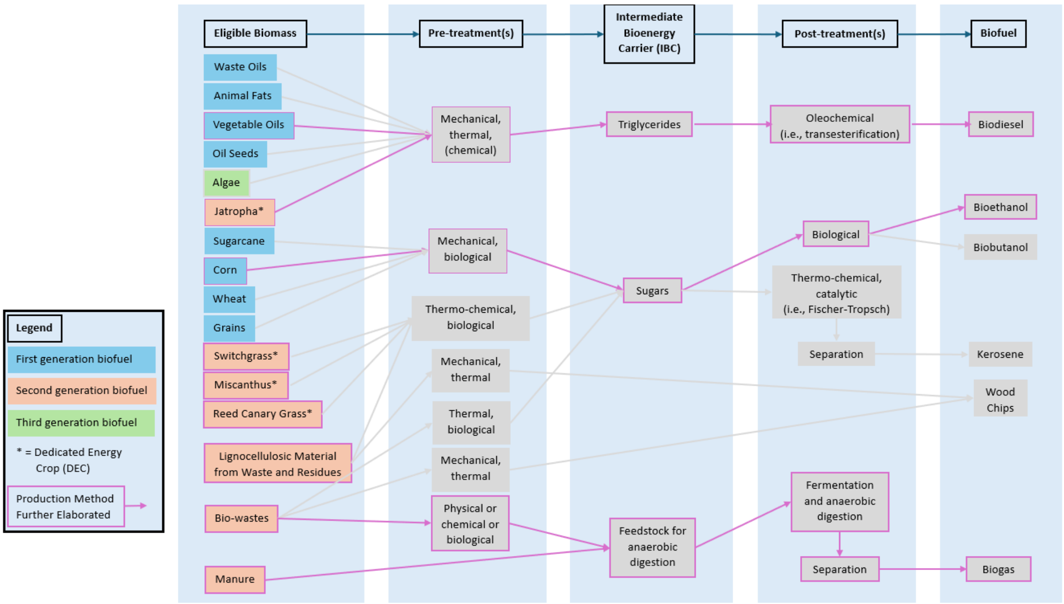

FIGURE 4.4: Comprehensive flow diagram illustrating the process of converting various types of biomass feedstocks into biofuels, divided into several stages: 'Eligible Biomass', 'Pre-treatment(s)', 'Intermediate Bioenergy Carrier (IBC)', 'Post-treatment(s)', and 'Biofuel'. The color code categorizes the feedstocks into first, second, and third generation biofuels. Feedstock highlighted with an asterisk '*' are categorized as Dedicated Energy Crops (DECs). The production methods outlined in pink are further discussed. Information used for the construction of this Figure was sourced from [155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166]

various biofuels can be produced from each feedstock type, there is typically a preferred production pathway that determines the specific type of biofuel generated, such as biogas, bioethanol, or biodiesel. The following subchapters will provide an overview of the three main generations of biofuels (first column of Figure 4.4), followed by the diverse methods used for their production including their pre- and post-treatments (columns 'Pre-treatment(s)), 'Intermediate Bioenergy Carrier (IBC)', and Post-treatment(s)' of Figure 4.4), and concludes with an environmental and economic analysis of each type of biofuel, focusing on their sustainability, technological requirements, and potential impact.

4.3.2 First Generation Biofuels

Exploring the Production and Impact of First Generation Biofuels: Bioethanol and Biodiesel

First generation biofuels are derived from edible biomass, such as sugarcane, corn, wheat, grains, oil-seeds, vegetable oils, rendered animal fats, and waste oils (see column 'Eligible Biomass' marked in blue of Figure 4.4) [156]. The key products of this generation are bioethanol and biodiesel. Bioethanol is produced through the fermentation of sugars extracted from starch-rich feedstock, while biodiesel results from the transesterification of triglycerides found in oil-rich feedstock [157].

Bioethanol, a substitute or blending agent for gasoline, is predominantly made from food crops like corn. The overall production of this process is the fermentation of sugars present in these crops (see Figure 4.4) [158]. It starts with the mechanical and biological pre-treatment of corn, where it is ground, slurrified, and liquefied in the presence of enzymes that releases starch for further use [158]. The starch is then saccharified into glucose (see the chemical equation 4.1), while simultaneously being fermented under anaerobic conditions (AD: Anaerobic Digestion) in the presence of yeast to yield bioethanol (see the chemical equation 4.2) [158].

$$(C_6H_{12}O_5)n + n\,H_2O \xrightarrow{AD} n\,C_6H_{12}O_6 \tag{4.1}$$

$$C_6H_{12}O_6 \xrightarrow{\text{AD, yeast}} CH_3CH_2OH \tag{4.2}$$

Taking corn as an examples, the theoretical yield of this process can be calculated with the following assumptions made:

- The starch content of dried corn is approximately 70 % [170]
- The water content in wet corn is approximately 15 % [171]
- 1.00 kg of starch with a molecular weight of 164.16 g/mol yields a maximum of 1.11 kg of glucose with a molecular weight of 180.16 g/mol (see the chemical equation 4.1)
- 1.11 kg of glucose yield a maximum of 0.57 kg of ethanol with a molecular weight of 46.07 g/mol (see chemical equation 4.2)
- The density of ethanol is 0.79 kg/l

Therefore, the maximum yield of bioethanol, that can be achieved from the saccharification of starch, followed by the fermentation of sugars contained in 100 kg of corn equals:

$$\frac{100\,\text{kg Corn} \times 0.70 \times 0.85 \times 1.11 \times 0.57}{0.79\,\text{kg/l}} = 42.81\,\text{Bioethanol} \tag{4.3}$$

Biodiesel serves as an alternative to petroleum diesel [159]. It is mainly produced from vegetable oils, with soybean oil being the largest contributor [159]. Although it can also be derived from waste products like animal fats and oil-rich waste, the majority (approximately 80%) comes from vegetable oils [159]. The production procedure follows a mechanical pre-treatment, where the feedstock gets dried, dehulled, ground, and flaked, before the oil gets extracted by pressing or chemical solvents [159]. The obtained triglycerides are subsequently converted to biodiesel via transesterification (see Figure 4.4) [172]. The reaction equation for this process is as follows (*chemical equation 4.4 gives the common names of the chemical molecules and equation 4.5 gives the chemical formula*):

$$\text{Triglyceride} + 3\,\text{Methanol} \xrightleftharpoons{\text{catalyst}} \text{Glycerol} + 3\,\text{Methyl ester} \tag{4.4}$$

$$C_3H_5(OOCR)_3 + 3\,HOCH_3 \xrightleftharpoons{\text{catalyst}} C_3H_8O_3 + 3\,RCOOCH_3, \tag{4.5}$$

where 'R' represents the fatty acid chains that are esterified with the glycerol backbone. Each R can be different depending on the specific fatty acid present in the triglyceride.

Taking soybean as an examples, the theoretical yield of this process can be calculated as follows with the following assumption made:

- The triglyceride content of dried soybean is approximately 20 % [173]
- The water content in wet soybean is approximately 13 % [174]
- 1.000 kg of triglyceride with a molecular weight of 219.21 g/mol yields a maximum of 1.014 kg of biodiesel with a molecular weight of 222.23 g/mol (see the chemical equation 4.5)
- The density of diesel is 0.85 kg/l

Therefore, the maximum yield of biodiesel, that can be achieved from the transesterification of triglyceride contained in 100 kg of soybean equals:

$$\frac{100\,\text{kg Soybean } \times 0.87 \ \times 0.20 \ \times 1.014}{0.85\,\text{kg/l}} = 20.7\,\text{l Biodiesel} \tag{4.6}$$

With a theoretical yield of 42.8 l bioethanol from 100 kg corn (33.8 wt% bioethanol) and 20.7 l biodiesel from 100 kg soybean (17.6 wt% biodiesel), these types of first generation biofuels offer a renewable alternative to fossil fuels, potentially reducing dependency on oil imports, enhancing energy security, and lowering greenhouse gas emissions [175, 176].

However, their production results in the diversion of food crops, which has sparked significant debate regarding food security. Critics argue that using crops for fuel rather than food can lead to increased food prices and exacerbate hunger in vulnerable regions [175, 177]. The cultivation of crops for biofuels demands substantial amounts of land, water, and fertilizers. This can lead to deforestation and loss of biodiversity through Direct Land Use Change (DLUC), as well as water scarcity [175]. Moreover, the use of fertilizers contributes to water pollution through runoff. Although biodiesel can be produced from waste products, its primary source remains vegetable oils, necessitating the cultivation of crops like soybeans [177, 178]. Some studies suggest that the energy required to produce first generation biofuels, considering the entire life-cycle from crop cultivation to fuel production, may diminish the net energy gain. This has raised questions about their overall efficiency and sustainability [178, 179].

To further explore the concerns of first generation biofuels (i.e., potential food scarcity, DLUC, environmental degradation, water scarcity, etc.), it is essential to understand their resource demands. This analysis is based on the calculation of a hypothetical scenario, explained in the next sub-chapter.

Hypothetical Calculation of Land, Water, and Fertilizer Requirements of First Generation Biofuels

To assess the practicality of substituting gasoline and diesel, traditionally derived from fossil fuels, with first generation biofuels like corn-based bioethanol and soybean-based biodiesel, this analysis is based on a hypothetical calculation. It takes into account the existing agricultural yields and production efficiencies, focusing on the required land, water, and fertilizer resources to fulfill Austria's entire fuel demand using these biofuels (see Figure 4.4).

The assumptions made in this study are as follows: Bioethanol, which is primarily used as a blending agent, is considered here as a complete substitute for gasoline. It is assumed that all gasoline consumption will be replaced by bioethanol derived from first-generation corn. Similarly, it is assumed that all diesel consumption will be substituted by biodiesel produced from first-generation soybean oil. The weight of a bushel of corn is assumed to be approximately 25.40 kg, with an average yield of about 173 bushels per acre [180, 181]. The theoretical yield of bioethanol from corn is assumed to be 33.8 wt% (as depicted in equation 4.3), representing the conversion efficiency from corn to bioethanol. For soybeans, the weight of a bushel is assumed to be approximately 27.21 kg, with an average yield of about 48 bushels per acre [182, 183]. The theoretical yield of biodiesel from soybeans is assumed to be 17.6 wt% (as depicted in equation 4.6), indicating the conversion efficiency from soybean oil to biodiesel.

The requirements defined for this study include the following: Water consumption for corn and soybean cultivation in Austria is approximated based on the agricultural share of 4% from the total annual water demand of 3.13 km^3, resulting in 0.1256 km^3 allocated for agriculture [184]. Fertilizer consumption is estimated based on the overall agricultural usage, which was 128.6 kg/hectare of arable land in 2021 [185]. Additionally, the fuel consumption in Austria in 2021 is considered, with approximately 1.9 billion liters of gasoline and 7.8 billion liters of diesel consumed [186]. These requirements are essential for evaluating the feasibility and impact of substituting gasoline and diesel with bioethanol and biodiesel, respectively.

1. **Total Weight of Feedstock per Hectare**

    - Corn (for bioethanol production)

$$\begin{aligned} &25.40\,\text{kg/bushel} \times 173\,\text{bushels/acre/year} \times 2.47\,\text{acre/hectare} \\ &\qquad = 10{,}803.7\,\text{kg/hectare/year} \end{aligned} \tag{4.7}$$

    - Soybean (for biodiesel production)

$$\begin{aligned} &27.21\,\text{kg/bushel} \times 48\,\text{bushels/acre/year} \times 2.47\,\text{acre/hectare} \\ &\qquad = 3{,}226.02\,\text{kg/hectare/year} \end{aligned} \tag{4.8}$$

	First Generation Bioethanol (from corn)	*First Generation Biodiesel (from soybean)*
Weight per Bushel of Feedstock (in kg)	25.40	27.21
Bushels of Feedstock per Acre per Year	173	48
Energy Content of Biofuel (in MJ/L)	21.2	32.8
Density of Biofuel (in kg/L)	0.789	0.88
Maximum Theoretical Yield (in %)	33.8	17.64
Area of Feedstock Required to Meet the Energy Target (in hectare/year)	619,662.91	12,870,808.81
Water Requirements	combined 641.0 billion liters	
Fertilizer Requirements	combined 79.6 - 1,655.2 million tons	

TABLE 4.4: Comparison of key parameters for first generation bioethanol (from corn) and first generation biodiesel (from soybean) including weight per bushel of feedstock, bushels of feedstock per acre per year, energy content of biofuel, density of biofuel. The results of the analysis include area of feedstock required to meet the energy target, water requirements, and fertilizer requirements.

2. **Calculation of Energy Requirements** In 2021, the consumption of gasoline and diesel in Austria amounted to 1.9 billion liters and 7.8 billion liters, respectively. This amounts to the following energy requirements.

    - Energy requirement to substitute 1.9 billion liters of gasoline by bioethanol based on corn

    $$1{,}900{,}000{,}000\,\mathrm{L} \times 32\,\mathrm{MJ/L} = 60{,}800{,}000{,}000\,\mathrm{MJ} \tag{4.9}$$

    - Energy requirement to substitute 7.8 billion liters of diesel by biodiesel based on soybean

    $$7{,}800{,}000{,}000\,\mathrm{L} \times 35\,\mathrm{MJ/L} = 273{,}000{,}000{,}000\,\mathrm{MJ} \tag{4.10}$$

3. **Theoretical Weight of Feedstock Required to Meet the Energy Targets**

    - Corn for Bioethanol Production

    $$\frac{60{,}800{,}000{,}000\,\mathrm{MJ}}{21.2\,\mathrm{MJ/L}} \times 0.789\,\mathrm{kg/L} \times \frac{100}{33.80} = 6{,}694{,}652{,}227.30\,\mathrm{kg} \tag{4.11}$$

    - Soybean for Biodiesel Production

    $$\frac{273{,}000{,}000{,}000\,\mathrm{MJ}}{32.8\,\mathrm{MJ/L}} \times 0.88\,\mathrm{kg/L} \times \frac{100}{17.64} = 41{,}521{,}486{,}643.44\,\mathrm{kg} \tag{4.12}$$

4. **Area of Feedstock Required to Meet the Energy Target**

- Corn for Bioethanol Production

$$\frac{6,694,652,227.30\,\text{kg}}{10,803.7\,\text{kg/hectare/year}} = 619,662.91\,\text{hectares/year} \tag{4.13}$$

- Soybean for Biodiesel Production

$$\frac{41,521,486,643.44\,\text{kg}}{3,226.02\,\text{kg/hectare/year}} = 12,870,808.81\,\text{hectares/year} \tag{4.14}$$

To meet Austria's 2021 fuel consumption needs with biofuels - specifically, replacing 1.9 billion liters of gasoline with bioethanol and 7.8 billion liters of diesel with biodiesel - extensive agricultural resources are required. Calculations indicate that approximately 619,663 hectares would be needed for bioethanol production from corn, and a staggering 12,870,809 hectares for biodiesel production from soybeans. As of 2021, Austria's agricultural land constitutes 31.48 % of its total land area, which translates to about 2,641,763 hectares [187]. The additional land required for bioethanol and biodiesel production would be 23 % and 387 % of the current agricultural land, respectively. These figures highlight the impracticality of meeting biofuel targets solely through domestic production, given the limited availability of arable land. Also, the production of these biofuels would significantly increase Austria's water consumption. Estimates suggest an additional 125.6 billion liters of water would be required, raising the total to 766.6 billion liters. This amount represents nearly a quarter of Austria's annual water usage, which stands at approximately 3,140 billion liters [184]. The demand for fertilizers would also see a substantial increase with an additional 79.6 - 1,655.2 million tons, annually, exacerbating environmental concerns such as eutrophication, where excess nutrients lead to harmful algal blooms in water bodies [185]. The consequences would be DLUC through the expansion of agricultural land for biofuel production, which can result in deforestation, loss of biodiversity, and disruption of carbon sequestration capacities in the soil and vegetation. The conversion of forests and natural landscapes into agricultural land for biofuel crops typically leads to a decline in native biodiversity. Additionally, the increased use of fertilizers and pesticides can lead to eutrophication, a process where excess nutrients lead to harmful algal blooms in water bodies, that then create dead zones in water bodies, where the oxygen level is too low to support marine life [188, 189, 190].

EU's Response to First Generation Biofuel Production Requirements

In response to growing concerns about the sustainability of first generation biofuels, the European Union (EU) has taken significant steps to regulate their production and promote more sustainable alternatives. This effort is encapsulated in the evolution of the Renewable Energy Directive (RED). Adopted in 2009, the original RED set a target for all Member States to achieve a 20 % share of renewable energy by 2020 [90]. This target included the use of biofuels in the energy mix. However, as concerns about the sustainability of first generation biofuels - those made from food and feed crops - intensified, it became clear that revisions were necessary. To address these concerns, the directive was revised and RED II was introduced in 2018 [94]. RED II specifically sets a cap on the contribution of first generation biofuels towards the EU's renewable energy targets. Under this new directive, the share of first generation biofuels cannot exceed the 2020 consumption levels of each Member State and must not surpass 7 % of the final energy consumption in road and rail transport by 2030. RED II also promotes the transition to second generation biofuels, which do not compete with food crops and are considered more sustainable [94]. Member States are mandated to ensure that at least 0.2 % of the energy consumed in road and rail transport by 2022 comes from these these types of non-food-competitive biofuels, with the target increasing to 3.5 % by 2030 [94].

Conclusion and Outlook of First Generation Biofuels

First generation biofuels, primarily derived from food crops like corn and soybeans, have been at the forefront of biofuel technology due to their relative technological readiness [191]. The production methods, such as fermentation for bioethanol and transesterification for biodiesel, are well-established and technically mature [191]. These processes are capable of large-scale implementation and have been integrated into the current energy infrastructure, particularly in the United States. However, the environmental sustainability of first generation biofuels is highly contentious. While they offer some reduction in greenhouse gas emissions compared to fossil fuels, this benefit is often offset by significant environmental costs [192]. The cultivation of biofuel crops frequently leads to land use changes that can result in deforestation, loss of biodiversity, and increased greenhouse gas emissions [175, 177]. Additionally, these biofuels require substantial inputs of water and fertilizers, which can lead to water scarcity and pollution issues. The reliance on food crops also raises ethical concerns regarding food security and food prices, as these crops are diverted from the global food supply [178]. Also, technological challenges arise during transesterification, due to the excess amounts of methanol (CH_3OH) required to increase yields, as can be seen in equation 4.5 [193]. Additionally, transesterification results in fuels that are still partially oxygenated and are therefore not a direct substitute for diesel. Moreover, a future problem could be the by-production of glycerol, that will overwhelm the market [193] Economically, first generation biofuels are often not viable without significant subsidies or regulatory support, as seen in the Renewable Fuel Standard in the United States [194]. The market for these biofuels is heavily influenced by policy decisions rather than market forces, leading to economic inefficiencies and potential market distortions [194]. Looking into the future, the outlook for first generation biofuels appears increasingly pessimistic. With growing awareness of their environmental impacts and the ethical issues related to food security, there is a shift in focus towards more sustainable alternatives [161]. Second generation biofuels, which utilize non-food biomass, are being explored as they do not compete directly with food crops and have a potentially lower environmental footprint [161]. If second generation biofuels do indeed reduce competition for food resources and minimize the environmental impacts is discussed in the next sub-chapter.

4.3.3 Second Generation Biofuels

The Complexities and Potential of Second Generation Biofuels

Second generation biofuels are derived from various types of non-food biomass, including lignocellulosic feedstocks, manure, bio-wastes, and dedicated energy crops (DECs, e.g., switchgrass, miscanthus, reed canary grass, etc.) grown on marginal land unsuitable for food production [160]. These biofuels are primarily produced from the structural tissues of plants, which consist of cellulose, hemicellulose, and lignin. Unlike first generation biofuels, which are made from food crops such as soybean and corn, second generation biofuels do not compete directly with food crops for agricultural land, which mitigates the food vs. fuel debate and reduces the impact on food prices and availability [161]. They also have reduced fertilization demands, which decreases the risk of eutrophication, compared to first generation feedstock [161]. However, it is important to note that while second generation biofuels do not directly compete with food and feed crops, they may lead to indirect land use change (ILUC) [195]. ILUC occurs when biofuel production on existing agricultural land displaces food or feed crop production, leading to increased food and feed production elsewhere. This displacement can lead to the conversion of grasslands and forests into croplands, resulting in increased greenhouse gas emissions and other environmental consequences [195] Moreover, the cultivation of second generation biofuels can be water-intensive. Estimates suggest that producing these biofuels may require between 2 to 84 times more water than is needed to produce an equivalent amount of energy from fossil fuels [196].

Initially, second generation biofuels were met with enthusiasm due to their use of non-food crops and lignocellulosic waste products, such as agricultural and forest residues, which have the potential of reducing greenhouse gas emissions by utilizing materials that would otherwise degrade and release carbon dioxide [161]. However, as the industry moves from theoretical models to practical implementation, several challenges become apparent. The production of second generation biofuels often reveals requirements that can be as demanding as those of first generation biofuels. This will be explained with multiple examples from production requirements of several second generation feedstocks.

Jatropha as a Biodiesel Feedstock: Challenges and Realities

Jatropha curcas is a plant that grows in tropical climates and was once celebrated as a promising candidate for second generation production, due to the ability to

1) Jatropha 2) Switchgrass 3) Reed Canary Grass 4) Miscanthus

FIGURE 4.5: Four types of second generation dedicated energy crops (DECs): Jatropha (1) primarily used for biodiesel production. Switchgrass (2), reed canary grass (3), and miscanthus (4) primarily used for bioethanol production.

grow on less fertile lands, overall rapid growth, and seeds rich in oil content (i.e., approximately 40 % fatty acids content), making it seemingly perfect for biodiesel production [162]. The production method is the same as the one described for first generation biodiesel production from soybean (see equation 4.5), with the only difference being the type of feedstock used (see Figure 4.4). Known also as the Barbados nut or Physic nut, its seeds are encased in pods, each harboring three seeds (see Figure 4.5). Despite its high oil yield potential, Jatropha's toxicity rendered it unsuitable for food or feed, positioning it as a non-competitive crop with food production and promising energy independence and economic uplifting for developing nations [162].

However, several significant issues emerged, which led to the dampening of the early enthusiasm: Jatropha cultivation faced numerous agronomic problems, including poorer than expected yields and susceptibility to pests and diseases. These issues were compounded by a lack of suitable agronomic knowledge and practices tailored to local conditions [197]. Also, the financial model underpinning Jatropha's large-scale cultivation and conversion into biodiesel faltered. High cultivation costs, coupled with the expensive processing of seeds into biodiesel and the requisite infrastructure, rendered many projects unprofitable. This economic shortfall was further deepened by the initial overestimation of yield potential and underestimation of input costs [197, 198]. The drive for Jatropha cultivation led to unintended social and environmental consequences, including land grabbing and the displacement of communities [199]. Contrary to initial claims of utilizing only marginal lands, there were instances where fertile lands, previously dedicated to food production, were converted into Jatropha plantations. Also, Jatropha biodiesel's cloud point [1] of –8 °C limits its use in colder climates, necessitating blending with other fuels to enhance fluidity [162]. This characteristic confines its utility to tropical regions, where temperatures do not plummet below freezing.

Despite these setbacks, efforts persist in enhancing Jatropha's viability as a biodiesel source. Research aimed at improving seed yields, pest and disease resistance, and refining the economic model of Jatropha biodiesel production continues [197, 199].

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[1] cloud point = temperature at which a liquid, such as diesel or biodiesel, begins to form solid crystals, resulting in a cloudy appearance. For biodiesel, the cloud point is generally higher than that of petroleum diesel due to the presence of saturated fatty acid esters.

However, the specter of indirect land use change (ILUC) and environmental degradation remains, underscoring the complex challenges that remain in realizing the full potential of Jatropha as a sustainable biofuel source.

Dedicated Energy Crops (DECs) and Lignocellulosic Waste Material as Bioethanol Feedstock: Challenges and Realities

Dedicated Energy Crops (DECs), such as switchgrass, reed canary grass and miscanthus, (see Figure 4.5) provide second generation feedstock for bioethanol production (see Figure 4.4), offering an alternative to first generation biofuels derived from corn (see production equation 4.1, and 4.2). These bioethanol feedstocks have gained global popularity in the early 2010s, especially in the United States, where the production of bioethanol is predominantly supported by the extensive cultivation of corn. To illustrate, in 2014, 6 % of the world's crop grains were utilized for biofuel production, and in the same year, 37 % of the U.S. corn grain contributed to the production of 14.3 billion gallons of bioethanol [200]. This production required about 27 million acres (10,926,512.3 hectares) of land primarily dedicated to corn cultivation, which represents approximately 1.2 % of the total land area of the U.S. [201]. Overall, 93.8 % of U.S. ethanol production originated from corn [202]. The significant allocation of land for corn cultivation, despite its relatively low energy balance (ranging from 1.25 to 2.6), has led farmers to seek alternative crops that offer better energy balances, require less land, and do not compete with food production. Miscanthus, in particular, has been identified as a promising DEC due to its low input costs, high potential for biomass yield, ability to thrive in nutrient-poor soils, and minimal production costs. In Northeast Arkansas, this resulted in a collaboration among Arkansas State University, MFA Oil/Biomass, and the U.S. Department of Agriculture's Biomass Crop Assistance Program aimed at harvesting 50,000 acres of miscanthus in 2018 [203]. However, despite the initial enthusiasm, the project did not succeed as planned, as the reality of converting miscanthus into biofuel proved more complex and costly than anticipated. The bioethanol production process from lignocellulosic biomass like miscanthus involves pre-treatment, enzymatic hydrolysis, and fermentation, which are technically challenging and expensive [204]. Second generation biofuel projects, including those involving miscanthus, have been prone to delays, cost overruns, and technical issues such as pre-treatment problems [205]. The project envisioned the construction of a conversion facility to turn the harvested miscanthus into biofuel. However, no processing center was ever built [205]. The absence of a dedicated facility for processing miscanthus into bioethanol significantly hindered the project's progress. Miscanthus is costly to transport, which made it economically unviable for farmers. The lack of a nearby processing facility exacerbated this issue, as the biomass would need to be transported over long distances [205]. Furthermore, federal funding for similar biofuel projects dried up, which likely affected the financial viability of the miscanthus biofuel project. Without sufficient financial support, the project could not sustain its operations or scale up production

[205]. The biofuel market and policy environment have been challenging for advanced biofuels like those derived from miscanthus. The Renewable Fuel Standard (RFS) in the U.S., for example, had ambitious targets for cellulosic biofuels that have not been met, reflecting broader difficulties in scaling up advanced biofuel production [205]. Additionally, the slow ramp-up time for cellulosic biofuels means that projects can take a decade or more from planning to full production, which is a significant barrier in a rapidly changing energy and policy landscape [205].

Lignocellulosic Material derived from agricultural residues and forestry wastes hold significant promise for alleviating some of the challenges associated with dedicated energy crops (DECs) in the production of second generation bioethanol. The primary appeal of these materials lies in their abundant availability and renewable nature. Unlike DECs, these types of feedstocks do not compete for arable land, nor do they contribute to indirect land use change (ILUC), making them a more sustainable option in the long term. These materials encompass a variety of non-food plant parts such as stems, leaves, husks, and wood residues. They are inherently rich in cellulose, hemicellulose, and lignin [163, 164]. However, their complex and intertwined network of fibers renders them highly resistant to chemical and physical degradation - a trait crucial for plant survival in natural environments where cells are often in hypotonic conditions, risking osmotic bursting [163]. Despite their advantages, the conversion of lignocellulosic materials into bioethanol is not without its challenges. The primary hurdle is the extensive and complex pre-treatment required to make these materials suitable for biofuel production [164]. Pre-treatment processes, which include intense chemical, physical, and biological methods, are necessary to break down the tough cellulose and hemicellulose into fermentable sugars [164]. These processes are crucial for the subsequent fermentation stage that produces bioethanol. Significant research and development efforts have been directed towards overcoming these technical challenges. Innovations in pre-treatment processes, such as hydrothermal and enzymatic treatments, have been developed to more effectively break down the cellulose and hemicellulose [163, 164]. However, despite these advancements, several persistent challenges hinder the widespread commercialization of lignocellulosic biofuels. The pre-treatment and conversion processes remain energy-intensive and costly, which makes the resulting biofuels less competitive with both fossil fuels and first generation biofuels [206, 207]. Moreover, the complexity of the biomass, variability in feedstock composition, and the difficulty in efficiently breaking down lignin remain significant obstacles [208]. Additionally, fluctuating policy landscapes and market uncertainties have also hindered the growth of the lignocellulosic biofuel industry. Changes in government policies, influenced by economic conditions and shifting political priorities, have led to instability in the biofuel market. This instability makes it difficult for producers to maintain profitability and attract investment [209]. Overall, while lignocellulosic materials from agricultural residues and forestry wastes offer a promising alternative to DECs for the production of second generation bioethanol, overcoming the technical, economic, and policy challenges is essential for realizing their potential in the biofuel industry.

Biowaste and Manure as Biogas Feedstock: Challenges and Realities

Biogas is primarily composed of methane (CH_4) and carbon dioxide (CO_2), with methane being the valuable components of energy production. The process of biogas generation involves the anaerobic fermentation of organic materials in three stages: hydrolysis and acidogenesis, acetogenesis, and methanogenesis [165, 166]. The initial phase, hydrolysis and acidogenesis, involves the breakdown of readily biodegradable substances. This is followed by acetogenesis, where heavily biodegradable substances are dissolved. The final stage, methanogenesis, transforms biodegradable substances into biogas. For substrates rich in lignocellulosic material, often found in biowaste, a pre-treatment step is necessary to make the material more amenable to digestion [166, 210]. This pre-treatment can be physical, chemical, or biological.

The theoretical biogas yield from organic materials during anaerobic digestion can be calculated using the chemical formula of the substrate involved. This yield is crucial for optimizing the production of renewable energy from organic waste, particularly lignocellulosic materials. The formula for theoretical biogas yield, represented by $B_{O,th}$, is derived from the stoichiometry of the organic compound undergoing digestion and is given by equation 4.15 [165, 166, 210] :

$$B_{O,th} = \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) \frac{22.4}{12n + a + 16b} \tag{4.15}$$

where n, a and b represent the number of carbon, hydrogen, and oxygen atoms in the molecular formula $C_2H_aO_b$ of the organic material.

$B_{O,th}$ varies significantly across different types of organic compounds due to their chemical structure. Ethanol (C_2H_6O), for example, exhibits the highest theoretical methane yield due to its simple structure and balance of carbon and hydrogen, followed by lipids ($C_{55}H_{98}O_6$, *for the averaged triglyceride*), proteins ($C_nH_{2n+1}NO_2$), and carbohydrates ($C_n(H_2o)_n$). Another factor that plays into the production yield of methane is the presence of nitrogen during the digestion process [211]. Nitrogen, primarily found in proteins, can lead to the production of ammonia (NH_3), which in high concentrations inhibits methanogenesis, potentially reducing biogas yield by up to 35 % [211]. This inhibition is particularly problematic in substrates with high protein content, like manure and certain biowaste, which typically have a protein content of 12 - 25 %. To ensure efficient biogas production, it is crucial to maintain an optimal carbon-to-nitrogen (C/N) ratio, generally between 20:1 and 30:1 [211]. This balance can be achieved by incorporating substrates with lower protein and higher carbon content, like lignocellulosic materials [166, 210]. However, as previously discussed, lignocellulosic biomass presents its own challenges, due to its complex, fibrous structure that resists microbial and enzymatic breakdown, impeding the hydrolysis phase of anaerobic digestion (AD). This resistance not only slows biogas production but also reduces methane yield. Pre-treatment methods for lignocellulosic biomass, while necessary to enhance digestibility, are energy-intensive, costly, and may produce inhibitory by-products that adversely affect the AD process. Additionally, incorporating lignocellulosic waste into AD can introduce operational challenges, such as increased viscosity, scum layer formation, and accumulation of undigested solids, leading to mixing difficulties, pipeline and pump blockages, and more frequent maintenance requirements [166, 210]. These issues can restrict microbial access to the biomass, thereby diminishing biogas production rates.

Despite these challenges, biogas production from manure and lignocellulosic waste has undergone significant technological advancements in recent years, leading to improved biogas yields and energy output. Innovations in reactor design have enhanced mixing and microbial-substrate contact, particularly in high-solids anaerobic digestion systems that accommodate higher solid contents without mass transfer limitations. Furthermore, the introduction of additives like enzymes or biochar can expedite the breakdown of organic materials and mitigate digestion inhibitors [165, 166, 210]. Economically, biogas plants can generate returns through the sale of biogas and the application of digestate as a bio-fertilizer, which improves soil fertility and reduces the reliance on chemical fertilizers. However, the financial viability of biogas projects depends on various factors, including the costs associated with feedstock collection, transportation, and handling, as well as substantial initial investments in plant infrastructure [165, 166, 210]. The development of the biogas sector is also influenced by policy and regulatory frameworks, where inconsistent policies and the absence of supportive incentives can impede biogas production growth [165, 166, 210]. Despite these challenges, biogas stands out as a highly promising second generation biofuel, offering numerous advantages such as no direct land use change (DLUC), no indirect land use change (ILUC), no fertilizer usage (in fact, it produces fertilizer), minimal water demand, high efficiency under optimal conditions, no biodiversity loss, and no deforestation.

Conclusion and Outlook of Second Generation Biofuels

Second generation biofuels, derived from non-food biomass such as lignocellulosic materials, have made significant strides in technological readiness. The transition from theoretical models to commercial-scale production, however, has encountered numerous challenges. While the first commercial-scale plants have been established, the overall adoption rate has been slower than anticipated. The complexity of processing lignocellulosic biomass, high initial capital costs, and the need for further technological advancements in pre-treatment and enzymatic hydrolysis processes are notable hurdles. Despite these challenges, ongoing research and development are gradually overcoming these barriers, suggesting a cautious optimism for the future scalability of these technologies. From an environmental perspective, second generation biofuels offer a more sustainable alternative to first generation biofuels because they do not compete directly with food crops for agricultural land and potentially reduce greenhouse gas emissions. However, the environmental sustainability of these biofuels is not without concerns. The production process is water-intensive and can lead to indirect land use changes that may negate some of the carbon emission benefits. Moreover, while they do not compete with food crops, the cultivation of energy crops can still lead to biodiversity loss and changes in land use that might have adverse environmental impacts. Continuous improvements in agricultural practices and better management of land use changes are critical to maximizing the environmental benefits of second generation biofuels. The economic feasibility of second generation biofuels is currently hindered by high production costs compared to fossil fuels and first generation biofuels. The financial viability of producing these biofuels at a competitive cost is still a major challenge, primarily due to the expensive pre-treatment processes required to break down lignocellulosic biomass. However, advancements in enzyme technologies and process efficiencies are expected to reduce costs over time. Economic sustainability will also depend heavily on supportive policies, such as subsidies and mandates, as well as on the global energy market dynamics, including oil prices and the economic valuation of reducing carbon emissions. The prospects for second generation biofuels depend on several factors. Technological breakthroughs that lower production costs and increase process efficiencies are critical. The industry could benefit significantly from enhanced international cooperation in research and development, as well as from consistent and supportive policy frameworks that encourage investment in biofuel technologies. Additionally, as global awareness of the environmental impacts of fossil fuels continues to grow, and as policies increasingly favor sustainable energy sources, second generation biofuels are likely to play a crucial role in the transition to a more sustainable energy landscape. Especially biogas production from manure and lignocellulosic waste represents a highly promising second generation biofuel due to its numerous environmental and economic benefits. Technological advancements have improved biogas yields and the efficiency of biogas plants in recent years, although challenges remain in terms of feedstock pre-treatment and operational issues in anaerobic digestion processes.

4.3.4 Third Generation Biofuels

Advancing Energy Sustainability: The Role of Third Generation Biofuels from Algae

Third generation biofuels are primarily produced from algal biomass, which includes both microalgae and macroalgae (seaweeds). These biofuels are considered a promising alternative to first and second generation biofuels, offering rapid growth rates, high photosynthetic efficiency, and superior areal productivity. Unlike first generation biofuels, which are derived from food crops, third generation biofuels do not compete with food production and have a minimal impact on food prices and availability [212, 213]. Algae can also be cultivated on non-arable lands, such as deserts, using non-potable water, thereby avoiding the land use conflicts associated with first and second generation biofuels [212, 213]. Additionally, algae can also grow throughout the year, resulting in higher productivity compared to other biomass sources that can only be harvested in certain seasons, as well as a high lipid content, which has the potential of offering higher biofuel yields per acre than first and second generation biofuel crops [214].

The production of third generation biofuels involves several steps, including the cultivation of algal biomass, harvesting, lipid extraction, and conversion of lipids into biofuels through processes similar to the transesterification of soybean for first generation biodiesel (see equation 4.5) [214]. To demonstrate their high production efficiency, a hypothetical calculation similar to the one from first generation is conducted (see subchapter 4.3.2).

Hypothetical Calculation of Land Requirements for Algal Biodiesel Production

To evaluate the land requirements and production efficiency of third generation algal biodiesel compared to first generation soybean biodiesel, the amount of land needed to produce sufficient quantities of biodiesel to replace Austria's annual diesel consumption, which totals 7.8 billion liters, is calculated. The process involves transesterification using algae, and the results are compared with those obtained from a similar calculation for first generation biodiesel (see subchapter 4.3.2). The assumptions for this analysis are the following:

- Microalgae have an oil content between 30 - 70 %, which translates under optimal growing conditions to an oil yield of 58,700 - 136,900 L/ha/year [215]
- The theoretical yield of the 1 kg oil equals 1.014 kg biodiesel (see equation 4.6). It is assumed that the average density of both is approximately the same.
- The energy content of biodiesel produced from microalgae equals 35.8 MJ/L
- Energy requirement to substitute 7.8 billion liters of diesel by biodiesel based on algae equal the one from first generation soybean (i.e., 273,000,000,000 MJ, see '2. Calculation of Energy Requirements' in chapter 4.3.2).
- The energy density of biodiesel based on algae is 0.86 kg/L [216].

1. **Liters of Algal Oil Required to Meet Hypothetical Energy Target** To cover Austria's annual diesel consumption of 7.8 billion liters, the following amount of liters of algal biodiesel are required:

$$\frac{273,000,000,000\,\text{MJ}}{35.8\,\text{MJ/L biofuel}} \times \frac{1\,\text{L oil}}{1.014\,\text{L biofuel}} = 7,520,412,548.35\,\text{L oil} \tag{4.16}$$

2. **Total Area Required**

- Lower limit of area needed for the cultivation of algae used for the complete and hypothetical substitution of Austria's diesel with biodiesel

$$\frac{7,520,412,548.35\,\mathrm{L\ oil}}{136,900\,\mathrm{L\ oil/ha/year}} = 54,933.62\,\mathrm{ha/year} \tag{4.17}$$

- Upper limit of area needed for the cultivation of algae used for the complete and hypothetical substitution of Austria's diesel with biodiesel

$$\frac{7,520,412,548.35\,\mathrm{L\ oil}}{58,700\,\mathrm{L\ oil/ha/year}} = 128,116.06\,\mathrm{ha/year} \tag{4.18}$$

3. **Comparison of Land Requirements Between First Generation Biodiesel Based on Soybean and Third Generation Biodiesel Based on Algae**

To substitute Austria's consumption of approximately 7.8 billion liters diesel in 2021, with biodiesel an agricultural area of between 54,933.62 - 128,116.06 hectares are required. This is only 0.4 - 1 % of the land area that were required if the diesel substitution were based on first generation biodiesel based from soybean (i.e., 12,870,808.81 hectares, see '4. Area of Feedstock Required to Meet the Energy Target' of subsection 4.3.2). As a reminder, the total agricultural area of Austria equals approximately 2,641,763 hectares. An addition of the above-mentioned range to grow the algal-based biodiesel substitute would only increase the agricultural land in Austria by 2.0 - 4.8 % (and not 387 % as it is for first generation biodiesel). This seems a lot more realistic and no fear for ILUC or DLUC, loss of biodiversity, and deforestation is necessary. Therefore, the challenges associated with the production of third generation biofuels are primarily technological and economic, rather than environmental aspects such as ILUC or DLUC and their respective consequences.

The Technological and Economic Challenges of Third Generation Biofuels

Selecting the most productive algae species and optimizing their growth conditions (light, temperature, CO_2, and nutrients) are significant challenges. Algae cultivation can be done in open ponds or closed photo-bioreactors, each with its own set of challenges, including contamination control, maintaining optimal growth conditions, and scalability [217]. One of the major technological hurdles is the efficient extraction of lipids from algae cells and their conversion into biodiesel through processes like transesterification. The energy balance of lipid extraction is concerning, as it often requires more energy than what the final biofuel product can produce. To maximize the biomass productivity of algae and enhance lipid yield per acre, genetic engineering and metabolic optimization are employed to increase lipid content without compromising growth [217, 218]. The sustainability of algae-based biofuel production is also under scrutiny. It is essential that the energy produced by algae biodiesel exceeds the energy consumed in its production process. Moreover, the carbon footprint of the entire production chain, from cultivation to fuel use, must be lower than that of fossil fuels to be considered a viable alternative. Although algae can grow in non-potable water, the large volumes required for extensive production pose significant risks to water quality and ecosystems. Efficient water management strategies are crucial to mitigate these impacts [219]. Supplying sufficient nutrients, especially nitrogen and phosphorus, for algae growth can be expensive and environmentally taxing. Utilizing wastewater streams for algae cultivation is a potential solution, but it introduces additional challenges related to contamination and consistency. The current cost of algae-based biodiesel production is higher than that of fossil fuels and other biofuels. Reducing production costs through technological innovations, optimizing processes, and developing co-products to improve the overall economics of algae biofuel production is necessary [220, 221, 222]. The economic viability of algae-based biodiesel is currently less competitive than that of fossil fuels and other biofuels, primarily due to high production costs. Reducing these costs through technological innovations, process optimization, and the development of co-products are necessary to improve the overall economics of algae biofuel production. Furthermore, the potential environmental impacts of large-scale algae cultivation, such as eutrophication, biodiversity loss, and the use of genetically modified algae strains, must be carefully managed to ensure the sustainable development of algae biofuels. Addressing these environmental concerns, alongside reducing production costs, is essential for the advancement of this technology [222, 223]. Finally, the commercial success of algae-based biodiesel depends on supportive policies, incentives, and a market ready to adopt these biofuels. Overcoming regulatory hurdles and establishing a clear market pathway are significant challenges that need to be addressed to facilitate the integration of algae biofuels into the energy market.

Conclusion and Outlook of Third Generation Biofuels

Third generation biofuels, derived from algal biomass, represent a significant advancement over first and second generation biofuels due to their non-reliance on food crops and ability to grow on non-arable land. The technological processes involved in their production include the cultivation of algal biomass, harvesting, lipid extraction, and conversion of these lipids into biofuels through processes like transesterification. Despite these advancements, there are significant technological challenges that need to be addressed. These include optimizing algal growth conditions, scaling up production systems (open ponds and photo-bioreactors), and improving lipid extraction methods which are currently energy-intensive and not yet cost-effective. Algal biofuels offer a promising reduction in carbon footprint compared to fossil fuels, primarily due to the feedstocks ability to efficiently sequester CO_2 during photosynthesis. Also, algae do not compete with food crops for land and can be cultivated using saline or wastewater, reducing the strain on freshwater resources.

However, large-scale cultivation poses risks such as eutrophication and biodiversity loss if not managed properly. The environmental sustainability of algae-based biofuels also depends on the life-cycle analysis of the production processes, from cultivation to fuel use, ensuring that the energy produced exceeds the energy consumed. Currently, the economic feasibility of third generation biofuels is less competitive compared to fossil fuels and other biofuels. High production costs, due to the technologically advanced processes required for algal cultivation and processing, are a significant barrier. The market for algae-based biofuels has not yet reached commercial viability without substantial subsidies or policy support. However, there is potential for cost reduction through technological innovations, process optimizations, and the development of co-products that could provide additional revenue streams.

The future of third generation biofuels looks promising but requires continued research and development to overcome current technological and economic barriers. Advances in genetic engineering and metabolic optimization may lead to more robust algal strains that offer higher lipid yields and faster growth rates. Economically, the integration of biorefinery concepts, where multiple products are derived from algal biomass, could improve the overall economics of algae biofuel production. Moreover, supportive policies and incentives are crucial to foster the growth of the algae biofuel industry. As technology advances and production costs decrease, algae biofuels have the potential to play a significant role in the transition to a more sustainable energy landscape, contributing to the reduction of greenhouse gas emissions and reliance on fossil fuels.

4.3.5 Comparative Analysis of First, Second, and Third Generation Biofuels

First generation biofuels, derived from edible biomass such as sugarcane, corn, wheat, grains, oil-seeds, vegetable oils, rendered animal fats, and waste oils, have been a significant focus in the renewable energy sector. The primary products of this generation are bioethanol, produced through the fermentation of sugars in starch-rich feedstock, and biodiesel, created via the transesterification of triglycerides in oil-rich feedstock. Economically, first generation biofuels are currently only viable with substantial subsidies and regulatory support. Their market presence is heavily influenced by policy rather than market forces, making them less attractive in a free-market scenario. The reliance on government intervention raises questions about the long-term sustainability of first generation biofuels as a competitive energy source. Environmentally, the production of first generation biofuels raises significant concerns. The diversion of food crops for biofuel production can threaten food security, particularly in regions already facing food scarcity. Additionally, the high demands for land, water, and fertilizers associated with these biofuels can lead to deforestation, loss of biodiversity, and water pollution. The net energy gain from first generation biofuels is also questionable due to the energy-intensive nature of their production processes. Consequently, the future prospects of first generation biofuels appear limited due to their significant economic and environmental challenges.

In contrast, second generation biofuels are derived from non-food biomass, including lignocellulosic feedstocks, manure, bio-wastes, and dedicated energy crops (DECs) like switchgrass and miscanthus. These biofuels utilize the structural tissues of plants, such as cellulose, hemicellulose, and lignin, and do not compete directly with food crops. Economically, the production of second generation biofuels is hindered by high costs due to the complex pre-treatment processes required to break down the lignocellulosic materials. However, their financial viability could improve with technological advancements and supportive policies that can reduce production costs and improve efficiency. Environmentally, second generation biofuels offer some advantages over their first generation counterparts. They reduce competition with food crops and have lower fertilization demands. However, potential indirect land use change (ILUC) and high water requirements pose significant challenges. Despite these issues, biogas produced from manure and lignocellulosic waste offers substantial environmental benefits, as it involves no direct land use change (DLUC) or biodiversity loss. The production of biogas from manure and lignocellulosic waste is especially promising, offering a viable pathway to reduce emissions and utilize renewable resources. Thus, second generation biofuels hold potential as a more sustainable alternative, particularly with ongoing research and technological advancements.

Third generation biofuels, produced from algal biomass, including microalgae and macroalgae, represent a promising advancement in biofuel technology. Algae can be cultivated on non-arable lands using non-potable water, and they offer high lipid content and superior areal productivity. Economically, the production of third generation biofuels is currently limited by high costs due to the advanced technological processes required. Significant technological innovations and process optimizations are necessary for these biofuels to become cost-competitive with other energy sources. Environmentally, third generation biofuels have minimal impact on food prices and availability, which is a significant advantage over first and second generation biofuels. They also have the potential for high productivity and lower land use. However, large-scale cultivation of algae poses risks such as eutrophication and biodiversity loss if not managed properly. Nevertheless, third generation biofuels show the most promise environmentally, with minimal land use conflicts and high productivity. Continued research and development are crucial to overcoming current economic barriers, and algae-based biofuels could significantly reduce greenhouse gas emissions and reliance on fossil fuels. In conclusion, while first generation biofuels have paved the way for renewable energy from biomass, their economic and environmental drawbacks necessitate the development of more sustainable alternatives. Second and third generation biofuels offer promising solutions, but they require further technological advancements and careful management to overcome their respective challenges. The future of biofuels lies in balancing economic viability with environmental sustainability to create a truly renewable and responsible energy source.

4.3.6 Current Applications and Future Predictions of First, Second, and Third Generation Biofuel Usage

The global biofuel industry is evolving rapidly, driven by the need to reduce greenhouse gas (GHG) emissions and dependence on fossil fuels. First generation biofuels, including bioethanol and biodiesel, are produced from food crops such as corn, sugarcane, and vegetable oils. Chemically, these biofuels are similar to their petroleum-based counterparts and can, therefore, be used in existing combustion engines with minimal modifications. Currently, first generation biofuels are primarily used in the transportation sector. Bioethanol is blended with gasoline, while biodiesel is mixed with diesel to reduce carbon emissions and enhance fuel security. The most common blends include E10 (10 % (bio)ethanol, 90 % gasoline), E15 (10.5 - 15 % (bio)ethanol), E85 (51 - 83 % (bio)ethanol), B5 (up to 5 % biodiesel), B20 (6 - 20 % biodiesel), and B100 (pure biodiesel). Consequently, GHG emissions are reduced by carbon dioxide (CO_2) absorption by the plants used to produce it. Bioethanol has an additional advantage to biodiesel, since the oxygen-molecule ethanol (C_2H_5OH) facilitating a more complete combustion, therefore reducing carbon emissions even further. The leading producers of first generation bioethanol and biodiesel are the United States (US) and Brazil. In the US, bioethanol is primarily derived from corn, while in Brazil, it is produced from sugarcane. Both countries also dominate the global biodiesel market, produced from soybean oil. To promote the use of these biofuels, the United States and Brazil have established blending mandates [224]. In the European Union (EU), mandates for biofuel usage also exist, but they specifically target second generation biofuels. This distinction arises from the 'food vs. fuel' debate, which has prompted a shift towards more sustainable feedstocks and production methods. One example of such a mandate is the European Union's Renewable Energy Directive (RED II), that aims to phase out biofuels with high (in)direct land use change (DLUC, ILUC) by 2030 [94].

Second generation biofuels, often referred to as 'advanced' biofuels, are produced from non-food biomass, including agricultural residues, woody crops, dedicated energy crops (DECs), and municipal solid waste. These biofuels address some of the sustainability issues associated with first generation biofuels and are therefore promoted in the RED II, with a target of at least 3.5 % in the transport sector by 2030 [94]. The most common second generation biofuel is cellulosic bioethanol, which is similarly used as first generation bioethanol as a blending agent in transportation gasoline. The actual usage of these advanced biofuels, however, varies significantly among EU member states. For example, in 2023, the Netherlands had a mandate of 2.4 % blending of advanced biofuels, while Germany's target was only 0.3 %. This indicates that while some countries are making more significant strides towards the targets, others are progressing more slowly. Therefore, achieving an average of 3.5 % for all EU member states by 2030 is ambitious. To realize this target, it will require substantial policy support, investment in new technologies, and scaling up production capacities, as well as technological advancements in conversion technologies, such as enzymatic hydrolysis and gasification are essential to improve the efficiency and cost-effectiveness of second generation biofuel. This will likely lead to increased production and adoption by 2030, as predicted by the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA).

Third generation biofuels, primarily derived from algae, offer significant advantages due to their high yield per unit area and the ability to grow on non-arable land, thereby avoiding direct and indirect land use changes. Currently, they are primarily used as transportation fuels, especially in the aviation and maritime sectors. For example, the International Maritime Organization has mandated the shipping industry to reduce CO_2 emissions by at least 40 % by 2030, which increased the interest in algae-derived fuels as replacements [225]. Despite these benefits, the commercialization of algal biofuels remains in its nascent stages, primarily due to high production costs and technological challenges. Within the European Union, several projects are dedicated to the development and commercialization of algal biofuels. However, these initiatives are still grappling with the aforementioned economic and technical hurdles. One notable project is the *EnAlgae* initiative, which involved multiple EU member states and aimed to develop sustainable technologies for algal biomass production. The project also sought to assess the potential for and barriers to the use of algal biofuels in reducing CO2 emissions and dependency on unsustainable energy sources in North West Europe. EnAlgae played a crucial role in advancing the understanding and development of algae-based technologies. By establishing a network of pilot plants, developing decision support tools, and conducting sustainability analyses, the project provided valuable insights and resources to support the growth of the algae sector in North West Europe. The findings and tools from EnAlgae continue to influence research and policy in the field of algae biomass production. Overall, both the IEA and IRENA recognize the potential of third generation biofuels. They recommend expanding the use of these biofuels in sectors such as aviation and shipping to reduce emissions and support economic recovery. Therefore, the commercialization of third generation biofuels holds significant promise for the future.

4.4 Synthetic Fuels as Alternative Fuels

4.4.1 Introduction to Synthetic Fuels

Synthetic fuels, also called synfuels, are created through chemical processes that transform raw materials like coal, natural gas, or carbon dioxide into usable fuels

[226]. These fuels can be derived from both renewable and non-renewable sources and mimic the chemical composition and energy content of traditional fossil fuels such as gasoline, diesel, and aviation fuel [99, 226]. These characteristics make them great potential candidates for mitigating climate change and enhancing energy security by diversifying energy sources.

Historical Context and Evolution

The development of synthetic fuels has a rich history that traces back to the late 18th century. The initial breakthrough in the creation of 'Coal to Gas' synthetic fuel occurred in 1792 when the Scottish engineer William Murdoch innovatively used coal distillation within an iron retort to illuminate his home [227]. This pioneering method involved heating coal in a closed container, which facilitated the release of flammable gases - a process now recognized as coal gasification. Murdoch's early experiments laid the groundwork for the broader application of this technology. By the early 19th century, the process had been refined and scaled up to produce coal gas, also known as town gas, primarily used in lighting methods, replacing existing oil and candle-based lighting methods [227]. The commercial deployment of coal gas began in earnest in 1812 when the London and Westminster Gas Light and Coke Company successfully used this technology to provide street lighting on Westminster Bridge in London [228]. This event marked the first widespread, public use of synthetic fuel. The process involved the heating of coal in an industrial oven, where it underwent carbonization, followed by the release of a mixture of gases including hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and carbon monoxide (CO). The gas mixture was then distributed through a network of pipes to the designated streetlamps, where it got combusted for lighting. The success in London quickly catalyzed the adoption of coal gas across other major cities in Europe and eventually around the world. The use of coal gas dramatically transformed urban life. It provided a brighter, more reliable light source that significantly improved the safety and extendability of nighttime activities in cities. Moreover, the infrastructure built to supply towns with coal gas also enabled future advancements in gas delivery and consumption, setting the stage for modern gas utilities and the eventual transition to natural gas. After the initial development of coal gasification techniques in the 18th and 19th centuries, the field of synthetic fuels expanded to include more complex processes and a broader range of feedstocks. In the Post-World War II era, the focus on synthetic fuels shifted significantly due to the abundant availability of crude oil, which reduced the economic viability of synthetic fuel production. However, the oil crises in the 1970s revived interest in synthetic fuels, particularly for countries heavily dependent on oil imports, like the Netherlands, France, Germany, and Belgium [229]. Despite these advancements, the consideration of synthetic fuels being more than just a diversifying energy source but also a solution to climate change has only become a priority in recent times. To illustrate the considerable effect synthetic fuels have had on historical emissions, a thought experiment is conducted in the next subchapter. This experiment explores the hypothetical scenario where coal gas is used to lighten all streetlamps in the EU today, estimating the emissions that would result in, highlighting the fact that not all synthetic fuels should be used as alternative fuels, when it comes to mitigating climate change.

Hypothetical Calculation to Demonstrate the Potential of Early Synthetic Fuels to Mitigate Climate Change

This thought experiment revisits the initial use of synthetic coal gas in street lighting, aiming to illustrate the potential carbon dioxide (CO_2) emissions produced, if all streetlamps in the EU were still lightened by the combustion of coal gas, today. It is then calculated how quickly these emissions alone could deplete the remaining Carbon Budget, defined by the Intergovernmental Panel on Climate Change (IPCC) as the maximum amount of cumulative net global anthropogenic carbon dioxide (CO_2) emissions that would result in limiting global warming to a given level with a specified probability, taking into account the effect of other anthropogenic climate forcers. The following assumptions are made:

- In the 19^{th} century, 300,000 cubic feet of coal gas, produced from 24 cubic meters of coal, illuminated 76,500 streetlamps each day [230, 231]
- The number of streetlamps used in the EU today, are estimated at 70 million, following an extrapolation of 7 million streetlamps in the UK [232]
- The composition of coal gas is as follows: 50.1 % H2, 30.5 % CH_4, 19.1 % CO_2, and 0.3 % of CO
- Coal gas is assumed to behave as an ideal gas, under standard conditions
- The combustion process of all composites of the gas is complete
- Greenhouse gases emitted through the mining and transportation of coal are not considered

Volume of coal gas needed to power 70 million streetlamps In the year 1817, London used approximately 300,000 cubic feet of coal gas daily to illuminate 76,500 streetlamps across the city [230, 231]. These numbers will be used to approximate the coal gas consumption of today's streetlamps within the European Union (EU), which are estimated at 70 million.

$$\frac{300,000\,\text{cubic feet of gas/day}}{76,500\,\text{lamps}} \times 70,000,000\,\text{lamps} \times 0.0283168\,\frac{\text{cubic meters}}{\text{cubic foot}} = \\ = 7.77\ \times 10^6\,\text{cubic meters of gas/day} \tag{4.19}$$

It would require 7.77 million cubic meters of coal gas each day, to power 70 million streetlamps distributed over the EU nowadays. This volume equals the following amount of moles:

Amount of moles contained in 7.77 million cubic meters of coal gas Assuming an ideal gas, the amount of moles contained in a certain volume at standard conditions can be calculated with the ideal gas law: PV = nRT

$$n = \frac{PV}{RT} = \frac{101325\,\mathrm{Pa} \times 7.77 \cdot 10^6\,\frac{\mathrm{m^3 of\ gas}}{\mathrm{day}}}{8.314\,\frac{\mathrm{m^3 \cdot Pa}}{\mathrm{K \cdot mol}} \times 298.15\,\mathrm{K}} = 3.23\ \cdot 10^8\,\frac{\text{moles of gas}}{\text{day}} \tag{4.20}$$

The amount of moles contained in 77.7 million cubic meters of gas equals 323 million moles of gas, which is required to power 70 million streetlamps, each day. Considering a coal gas composition of 50.1 % hydrogen (H_2), 30.5 % methane (CH_4), 19.1 % carbon dioxide (CO_2), and 0.3 % carbon monoxide (CO), the following amounts of moles CO_2 are released upon combustion of the gas:

Theoretical CO_2-equivalent emissions from coal gasification The combustion of coal gas releases CO_2 in the following molar ratio: $2\,H_2\,(g) + O_2(g) \longrightarrow 2\,H_2O(g)$ $CH_4(g) + 2\,O_2(g) \longrightarrow CO_2\,(g) + 2\,H_2O(g)$ $2\,CO(g) + O_2(g) \longrightarrow 2\,CO_2(g)$ Considering the composition of coal gas, 1 mole of CO_2 gets released for 1 mole of CH_4, 1 mole of CO, and 1 mole of CO_2, respectively. The CO_2 emissions from the combustion of 323 million moles of coal gas are therefore:

$$\begin{aligned}(0.305 + 0.191 + 0.003)\frac{\text{mol CO2 emissions}}{\text{mol of gas}} \times 3.47\ \cdot 10^8\frac{\text{moles of gas}}{\text{day}} \\ = 1.61\ \cdot 10^8\frac{\text{mol CO2 emissions}}{\text{day}}\end{aligned} \tag{4.21}$$

The combustion of 323 million moles of coal gas results in the emission of 161 million moles of carbon dioxide (CO_2) daily. To assess the implications of these emissions on climate change, an analysis is conducted to estimate the duration required for solely these emissions to exhaust the global remaining carbon budget, which is quantified at 100 gigatons (Gt) of CO_2 from the beginning of 2023, with an 83% level of confidence [233]. In this theoretical scenario, it is posited that all sources of greenhouse gas emissions, with the exception of those emanating from the EU's streetlamps, are abruptly halted. This speculative framework is employed to ascertain the period within which the remaining carbon budget, as defined by the IPCC, would be entirely consumed by emissions solely from street lamps. Since the remaining carbon budget is given in gigatons CO_2 equivalent, the moles of CO_2 emitted each day by the combustion of coal gas to illuminate 70 million streetlamps is converted into gigatons as well, using it molar weight of 44.01 g/mol:

$$1.61\ \cdot 10^8\,\mathrm{mol\ CO2/day}\ \times 44.01\,\mathrm{g/mol}\ \times \frac{1\,\mathrm{Gt}}{1 \cdot 10^{15}\mathrm{g}} = 7.09 \cdot 10^{-6}\,\mathrm{Gt\ CO2/day} \tag{4.22}$$

The remaining carbon budget of 100 GT CO_2 would therefore be depleted after the following time:

$$\frac{100\,\text{Gt CO2-eqv}}{7.09 \cdot 10^{-6}\,\text{Gt CO2-eqv/day}} = 14.1 \cdot 10^{6}\,\text{days} \approx 39,000\,\text{years} \tag{4.23}$$

With a daily emission rate of 7,090 tonnes of CO_2, it would require approximately 39,000 years to exhaust the carbon budget solely through the emissions generated by the illumination of 70 million streetlamps with coal gas from the 19th century. At first glance, this figure may appear insubstantial, particularly when considering that it constitutes merely 0.795% of the EU's daily emissions. However, when contextualized, these emissions equate to the daily carbon footprint of nearly half a million individuals. Also, it is assumed that no incomplete combustion is taking place, which would otherwise release the more potent greenhouse gases methane, depleting the remaining carbon budget significantly faster (i.e., the GWP of methane is 27.9, which makes it 27.9 times more potent than carbon dioxide, see Table 2.1). In practical scenarios, complete combustion only rarely occurs, when sufficient oxygen is supplied and an adequate mixing of fuel and air is given. This scenario most likely did not occur in the 19th century, and it can therefore be assumed that the greenhouse gases CH_4 and CO were emitted alongside CO_2, reducing the approximated 39,000 years to deplete 100 Gt CO_2 equivalent emissions significantly. Moreover, the endeavor to reduce carbon emissions is inherently a collective one. Achieving a reduction of 7,090 tonnes of CO_2 per day represents a significant accomplishment. Such a reduction can only be realized through the adoption of carbon-neutral or carbon negative energy sources, as it will be explained in the following subchapter.

The Potential of Modern Day Synthetic Fuels in Mitigating Climate Change: E-fuels

In recent years the EU has realized, that the greatest potential for carbon neutral or even carbon negative synthetic fuels lies in a specific type, called electrofuels, also know as 'e-fuels'. Although there is no clear consensus in the political community about the difference between e-fuels and synthetic fuels, and the terms are often falsely used interchangeably, the scientific definition of e-fuels is as follows:

> E-fuels are a specific subset of synthetic fuels produced from (re)captured carbon dioxide (CO_2) and water (H_2O) using renewable or decarbonized electricity.

E-fuels have been discussed and promoted in various forms for several decades, but have only gained special momentum after the *Dieselgate* [2] scandal in 2015, which

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[2] The "Dieselgate" scandal, also known as "Emissionsgate," refers to the controversy that erupted in 2015 when the United States Environmental Protection Agency (EPA) discovered that Volkswagen Group (VW) had installed software in its diesel vehicles to cheat emissions tests. This software, known as a "defeat device," activated emissions controls only during laboratory testing, allowing the vehicles to meet regulatory standards. However, during normal driving conditions, the emissions controls were

exposed widespread cheating on emissions tests by automakers [234]. This scandal significantly shifted the focus towards cleaner alternatives, including e-fuels, as part of a broader strategy to meet stricter CO_2 emissions standards in the EU. This is reflected in e.g., the ReFuelEU Aviation proposal [235], released as part of the 'Fit for 55' climate package, which sets mandates for the minimum uplift of e-fuels, aiming to reach 35 % by 2050. Having the potential of being the most promising synthetic fuel for mitigating climate change, e-fuels will be the only types of synthetic fuels considered from now on.

4.4.2 Types of E-Fuels and their Production: Power-to-Gas (PtG) and Power-to-Liquid (PtL) Technologies

There is a vast variety of different types of e-fuels, including e-methane, e-methanol, e-diesel, e-kerosene, e-gasoline, and e-hydrogen. The common starting materials for all e-fuels are captured carbon dioxide (CO_2) and water (H_2O), with the specific process conditions determining the type of e-fuel produced [236]. The typical production process involves the hydrogenation of CO_2 and/or carbon monoxide (CO), obtained through a reverse water-gas shift reaction (see equation 4.24) [236]. The following reaction mixtures H_2 + CO_2 and/or H_2 + CO (i.e., syngas) are then subjected to various reaction conditions, enabling the production of the majority of e-fuel, that can be broadly categorized into two main groups: power-to-gas (PtG) and power-to-liquid (PtL) [237].

PtG: E-Hydrogen and E-Methane

PtG is a technology that that converts electrical energy into chemical energy in the form of gas [237]. This process typically involves the use of renewable electricity to produce hydrogen through water electrolysis (i.e., green hydrogen, see subchapter 4.2.3: *'Production and Potential of Green and Pink Hydrogen'*). The hydrogen can then be used directly as a fuel, thereby qualifying as both green hydrogen and **e-hydrogen**. Alternatively, it can be further processed with carbon monoxide (CO) and/or carbon dioxide (CO_2) to produce **e-methane** (CH_4) via methanation, using a nickel or nickel-iron catalyst at 250 - 450 °C and atmospheric pressure [237, 238]. The produced gases can be stored and used in various applications, such as in the natural gas grid, for heating, or as a fuel for vehicles [237]. The primary advantage of PtG is its ability to store excess renewable energy and provide a flexible and scalable solution for energy storage and grid balancing.

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turned off, causing the vehicles to emit nitrogen oxides (NOx) at levels up to 40 times higher than the legal limit. The scandal affected approximately 11 million vehicles worldwide and led to significant financial penalties, legal actions, and a severe reputational impact on VW and the broader automotive industry

	E-Methane	**E-Methanol**	**E-Diesel, E-Kerosene, E-Gasoline**
Primary Production Process	Methanation of syngas (i.e., H2 + CO) and/or H2 + CO2	Hydrogenation of CO and/or CO2	Fischer Tropsch synthesis utilizing syngas
Catalysts	Nickel, Nickel-Iron	Cu/ZnO/AlO3	Iron- or cobal-based with specific promoters
Reaction Conditions	250 - 450 °C at atmospheric pressure	200 - 300 °C at elevated pressures	Around 180 - 350 °C at elevated pressures (20 - 60 bar) *High T and low P favor the formation of lighter hydrocarbons*

TABLE 4.5: Summary of production processes, catalysts, and reaction conditions for sustainable synthetic fuels, including e-methane, e-methanol, e-diesel, e-kerosene, and e-gasoline.

PtL: E-Methanol, E-Diesel, E-Kerosene, and E-Gasoline

Power-to-Liquid (PtL) is a process that converts electrical energy into liquid fuels [237]. Similarly to PtG e-fuels, green hydrogen is combined with either CO_2 and/or CO and subjected to various reaction conditions, producing liquid hydrocarbons. PtL fuels are considered a viable option for large-scale decarbonization in the transportation and aviation sectors, as they can be used in existing engines and infrastructure with minimal modifications. The several types of PtL e-fuels are all primarily produced via Fischer-Tropsch processes under the varying conditions as can be seen in Table 4.5: **E-methanol** is produced via the hydrogenation of CO_2 and CO using primarily Cu/ZnO-based systems temperatures ranging between 200 - 300 °C and elevated pressures [239]. The production of **e-diesel**, **e-kerosene**, and **e-gasoline** follows the Fischer-Tropsch synthesis (FTS) process, which will be explained in great detail in the following.

Fischer-Tropsch Synthesis (FTS) is a well-established chemical reaction process used to convert synthesis gas (commonly known as syngas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2)) into hydrocarbons [236]. These hydrocarbons can range from simple gases to complex waxes, with the main products being linear alkanes and alkenes, primarily used for producing PtL fuels, like e-diesel, e-kerosene, and e-gasoline [240]. While this process plays a crucial role in the production of several synthetic fuels and biofuels from coal, natural gas or biomass (see Production pathway of kerosene from second generation feedstock in Table 4.4), in the following only the production of e-diesel, e-kerosene, and e-gasoline will be considered (see Table 4.5).

The basic mechanism of the Fischer-Tropsch process involves the catalytic conversion of syngas into different lengths of hydrocarbon chains [241]. This process is facilitated by a metal catalyst, that is typically iron- or cobalt-based. These catalysts enable the polymerization of carbon monoxide, which is primarily produced from the hydrogenation of CO_2 through the reverse water-gas shift reaction (RWGS), as shown in equation 4.24. In equation 4.25, the subsequent polymerization reactions are depicted. The temperatures and pressures range between 180 - 350 °C and 20 - 60 bar, respectively, depending on the desired chain-length of the produced hydrocarbons [240, 242]. Higher temperatures (200 - 350 °C) favor the formation of lighter hydrocarbons such as e-gasoline, while lower temperatures (180 - 240 °C) promote the production of heavier hydrocarbons like e-diesel, and e-kerosene [243]. Contrarily, higher pressures (20 - 60 bar) increase the chain growth probability, favoring the formation of heavier hydrocarbons, whereas lower pressures (< 20 bar) favor lighter hydrocarbons [243]. Another factor that plays into the type of e-fuel produced, is the H_2/CO ratio of the supplied syngas. A higher ratio promotes the formation of longer-chain hydrocarbons. Also, the choice of catalyst and its properties (e.g., particle size, acidity, and metal-support interactions) significantly influence the chain growth distribution [243].

Further downstream processes include the refinement of the obtained hydrocarbons from the Fischer Tropsch process through hydrocracking and isomerization. Again, higher temperatures and lower pressures favor lighter hydrocarbons like e-gasoline, and lower temperatures and higher pressures promote the formation of heavier hydrocarbons like e-diesel [236, 244]. During hydrocracking, larger molecules get broken down into smaller, more useful molecules in the presence of H_2 and a suitable catalyst, as depicted in equation 4.26. To improve the fuel quality even further, the octane number is enhanced by an isomerization reaction in the presence of a catalyst. In this reaction the carbon atoms are rearranged without changing the number of carbon and hydrogen atoms, but producing isomers with the same molecular formula and different structures, as can be seen in equation 4.27.

$$Hydrogenation : \mathrm{nCO_2} + \mathrm{nH_2} \xrightleftharpoons{\text{catalyst}} \mathrm{nCO} + \mathrm{nH_2O} \tag{4.24}$$

$$Polymerization : \mathrm{nCO} + (2\mathrm{n}+1)\mathrm{H_2} \xrightarrow{\text{catalyst}} \mathrm{C}_n\mathrm{H}_{2n+2} + \mathrm{nH_2O} \tag{4.25}$$

$$Hydrocracking : \mathrm{C}_n\mathrm{H}_{2n+2} + \mathrm{nH_2O} + \mathrm{H_2} \xrightarrow{\text{catalyst}} \mathrm{C}_{n-x}\mathrm{H}_{2(n-x)+2} + \mathrm{C}_x\mathrm{H}_{2x+2} \tag{4.26}$$

$$Isomerization : \mathrm{C}_x\mathrm{H}_{2x+2} \xrightarrow{\text{catalyst}} \mathrm{C}_x\mathrm{H}_{2x+2}\,\text{isomer} \tag{4.27}$$

Equations 4.24, and 4.25 depict the FTS of fuels and illustrate that for every n molecules of carbon dioxide and ($3n$+1) molecules of hydrogen, a hydrocarbon containing n carbon atoms and n molecules of water are produced. Yet, this yield is only achieved theoretically. Practically, the yield is reduced from undesirable side reaction, like the Water-Gas Shift (WGS) reaction (i.e., reverse hydrogenation, depicted in equation 4.24), that consumes H_2 and CO, ultimately reducing the amount of syngas available for the subsequent polymerization. Also, the catalysts employed throughout the FTS can deactivate over time due to factors like sintering, poisoning, and carbon deposition, which decreases the activity and selectivity of the catalyst, leading to lower yields of desired liquid products [245]. Additionally, a further reduction of the yield is obtained through the separation and purification of the product stream after polymerization [246]. To minimize yield loss, research is focused on mitigating the WGS reaction, improving catalyst stability, and optimizing separation processes [246].

4.4.3 Assessment of Fischer-Tropsch E-Fuels

Fischer-Tropsch e-fuels present a sustainable alternative to conventional fossil fuels, as they are produced from syngas derived from green hydrogen (H_2) and captured carbon dioxide (CO_2). The fuels synthesized via the Fischer-Tropsch process exhibit superior quality compared to conventional fuels, boasting higher cetane numbers, lower aromatic content, and fewer impurities, which result in cleaner combustion [247]. Recent advancements in catalyst design, such as the development of bifunctional catalysts and the application of machine learning, have significantly improved the efficiency, selectivity, and stability of the Fischer-Tropsch process [248]. Additionally, the use of additive manufacturing has enabled the creation of more efficient reactor designs with enhanced heat management and higher productivity, potentially making smaller-scale operations more feasible [246].

However, the Fischer-Tropsch process faces substantial challenges, including high capital and operational costs that necessitate large-scale facilities to achieve economic viability, posing a significant barrier to widespread adoption [245]. The production of green hydrogen, a crucial feedstock for the Fischer-Tropsch process, remains expensive, impacting the overall cost-effectiveness of e-fuel production (see chapter 4.2.5 *'Comparative Analysis of Hydrogen Production, Storage, and Transportation'*). Also, Carbon Capture Utilization (CCU) technologies show for high energy requirements, scalability issues, and economic unviability. Furthermore, catalyst deactivation and degradation over time can reduce the efficiency and productivity of the Fischer-Tropsch process, necessitating ongoing research and development to improve catalyst stability [245].

Despite these challenges, the increasing global focus on decarbonization and the transition to sustainable energy sources presents a significant opportunity for the adoption of Fischer-Tropsch e-fuels as a low-carbon alternative to conventional fuels [249]. The utilization of captured carbon dioxide as a feedstock for the Fischer-Tropsch process through CCU technologies can contribute to mitigating greenhouse gas emissions while providing economic incentives for industries [249]. The European Union's (EU) strategic funding and policy initiatives, such as the Industrial

Carbon Management Strategy and the Horizon Europe program, support the development and deployment of CCU technologies, including Fischer-Tropsch synthesis (FTS), creating favorable conditions for innovation and investment. Ongoing research and development efforts in areas such as catalyst design, reactor engineering, and process optimization can further enhance the efficiency and cost-effectiveness of the Fischer-Tropsch process, making it more competitive with conventional fuel production methods [249]. Specifically, modern research focuses on developing bifunctional catalysts that can perform polymerization (see equation 4.25), hydrocracking (see equation 4.26), and isomerization (see equation 4.27) simultaneously, thus enhancing the one-stage production of liquid hydrocarbons from syngas [241]. These catalysts typically feature a combination of metal and acid sites, with materials like zeolites, clays, alumina, silica, aluminosilicates, and carbons being common supports [240, 241]. For instance, cobalt-based catalysts, which are particularly suitable for e-diesel production, can be optimized by adjusting the ratio of metallic to acidic components, which affects the selectivity towards specific hydrocarbon fractions like C11–C18, crucial for diesel production [240].

Nevertheless, potential competition from alternative sustainable fuel technologies, such as biofuels or hydrogen fuel cells, could pose a threat to the widespread adoption of Fischer-Tropsch e-fuels if these alternatives become more cost-effective or technologically superior [245]. Fluctuations in the prices of feedstocks, such as syngas or captured carbon dioxide, could impact the economic viability of Fischer-Tropsch e-fuel production, making it less competitive compared to conventional fuels. Regulatory and policy changes, particularly those related to carbon pricing or emissions trading schemes, could affect the economic incentives for CCU technologies and the Fischer-Tropsch process [245]. Additionally, public perception and acceptance of e-fuels as a sustainable alternative may be a challenge, especially if concerns arise regarding their environmental impact or production processes.

4.4.4 Current Applications and Future Predictions of E-Fuels

Currently, e-fuels are in the early stages of deployment, with several pilot projects and research initiatives underway around the world. One notable project is the e-fuel plant in Patagonia, Chile, being developed by Siemens Energy and Porsche, along with other partners. This plant, known as the Haru Oni project, represents a pioneering effort in the production of nearly carbon-neutral fuels, leveraging the region's abundant wind energy resources. It is set to produce 130,000 liters of e-fuel in 2022, with plans to scale up production to 55 million liters per year by 2025 and further 550 million liters by 2027 [250]. The production process involves the production of green hydrogen combined with carbon dioxide (CO_2) captured directly from the air, to firstly produce e-methanol, which is then converted into e-gasoline [250]. The price per liter is projected to be about €1.60 per liter in 2026, potentially decreasing to one euro per liter by 2030 as the technology matures and scales up [251]. This initiative highlights the growing interest and investment in e-fuel technology as a viable alternative to traditional fossil fuels.

The aviation industry is one of the primary sectors exploring the use of e-fuels, given the challenges associated with electrifying flight due to the weight and energy density limitations of batteries. E-fuels offer a viable alternative to conventional jet fuel, with the potential to significantly reduce the carbon footprint of air travel. In the automotive sector, e-fuels are being tested as a cleaner alternative to gasoline and diesel, providing a way to decarbonize existing fleets of vehicles without the need for electrification. Additionally, e-fuels are being considered in other sectors where electrification is challenging, such as heavy industry and maritime transport. The high energy density of e-fuels makes them suitable for applications requiring long-range or high-power output, such as shipping and heavy-duty trucking. In these sectors, e-fuels could play a crucial role in reducing emissions and transitioning to a more sustainable energy system.

Looking to the future, the potential for e-fuels to contribute to global decarbonization efforts is significant. As renewable energy capacity continues to grow and technologies for capturing CO_2 improve, the production of e-fuels is expected to become more economically viable. This could lead to increased adoption across various sectors, from transportation to industrial processes. One of the key challenges facing the widespread adoption of e-fuels is the need for substantial investments in production facilities and infrastructure. However, with supportive policies and incentives, it is possible to accelerate the development and deployment of e-fuels. Governments and industry stakeholders are increasingly recognizing the importance of e-fuels in achieving net-zero emissions targets, leading to greater collaboration and investment in this area. In the transportation sector, e-fuels could complement electrification efforts, providing a solution for applications where batteries are less suitable. For example, long-haul trucking, aviation, and maritime transport could all benefit from the high energy density and easy storage of e-fuels. As production costs decrease and technology matures, e-fuels could become a competitive alternative to fossil fuels, driving a significant reduction in greenhouse gas emissions. In conclusion, e-fuels represent a promising avenue for reducing global carbon emissions, with potential applications across a wide range of sectors. While challenges remain in terms of production costs and infrastructure development, the future of e-fuels is bright.

4.5 Conclusion - Comparative Assessment of Hydrogen, Biofuels, and Synthetic Fuels as Alternative Fuels

Hydrogen, biofuels, and synthetic fuels have emerged as promising alternatives to fossil fuels, each with its unique strengths, weaknesses, opportunities, and threats.

While these alternative fuels offer potential solutions to address environmental concerns and reduce greenhouse gas emissions, they also face challenges that must be addressed to ensure their widespread adoption and long-term sustainability.

Hydrogen stands out as a clean and efficient fuel source, with high energy content by weight and zero direct emissions during combustion. Its versatility allows it to be used in fuel cells for electricity generation or in internal combustion engines, making it a viable option for various applications, including transportation and power generation. However, the production, storage, and transportation of hydrogen pose significant challenges. Currently, the most common methods of hydrogen production are energy-intensive and costly, particularly for green hydrogen produced via electrolysis using renewable energy. Additionally, hydrogen's high diffusivity and low ignition energy raise safety concerns, necessitating special handling and containment measures.

Biofuels, derived from renewable resources, offer the potential for carbon neutrality when produced sustainably. They can be compatible with existing vehicles and fuel infrastructure, reducing the need for significant modifications. However, first generation biofuels, produced from food crops, have raised ethical concerns due to the 'food vs. fuel' debate and their potential impact on food prices and availability. Furthermore, the production of biofuels can lead to deforestation, loss of biodiversity, and water pollution if not managed responsibly. Second and third generation biofuels, derived from non-food biomass and algae, aim to mitigate these issues, but they face challenges related to land use, water consumption, high production costs., and technological readiness.

Synthetic fuels, particularly e-fuels, offer a promising solution for reducing the environmental impact of fuels by utilizing captured CO_2 and green hydrogen in their production process. They can be designed to mimic conventional fuels, allowing for compatibility with existing engines and infrastructure, which makes them great candidates for reducing greenhouse gas emissions in hard-to-electrify sectors. However, the production of synthetic fuels involves complex chemical processes and advanced technologies that are still under development, resulting in high production costs and technological complexity.

While each alternative fuel presents unique advantages and challenges, their widespread adoption and long-term viability will depend on several factors. Technological advancements, supportive policies and incentives, and investments in infrastructure will be crucial in reducing production costs and improving efficiency. Additionally, addressing environmental concerns, such as land use change and water consumption, will be essential for ensuring the sustainability of these alternative fuels.

Ultimately, the transition towards a more sustainable energy system may require a combination of these alternative fuels, tailored to specific applications, sectors, and locations. Ongoing research, development, and collaboration among stakeholders will be essential in overcoming the challenges and realizing the full potential of these alternative fuels in the pursuit of a more sustainable and environmentally responsible energy future.

Chapter 5

Case Study: RCG Reach Stackers and Alternative Fuels

5.1 Rail Cargo Group's Commitment to Sustainable Operations

The Rail Cargo Group (RCG) stands as a pivotal player in the European rail logistics sector. With its roots deeply embedded in the ÖBB (Austrian Federal Railways) infrastructure, RCG extends its operations across 18 countries, from the North Sea to the Black Sea, and the Mediterranean [252]. This expansive reach is facilitated by the group's presence in 13 European countries through its traction companies, alongside its own container terminals and logistics centers [252]. The core competencies in RCG's railway logistics are structured around five business areas: rail forwarding with specialist sector competence, carrier for in-house traction provision, wagon rental, rolling stock maintenance, and operator for high-frequency long-distance routes [252]. The group's vision of being the sustainable logistical backbone of the economy underscores its dedication to a green future and positions it as a key architect in the anticipated renaissance of rail freight in the 2020s [252, 253]. In alignment with its commitment to sustainable operations, RCG has explicitly outlined its dedication to conducting business with environmentally responsible behavior, aiming to prevent pollution and make a substantial contribution to environment and climate protection [254]. A notable manifestation of this commitment is the initiative to equip their container reach stackers with alternative fuels. A more detailed insight into the operations of RCG's container terminal will be provided in the next sub-chapter.

5.2 RCG Container Terminals

RCG has 15 container terminals situated across Austria (AT), Slovenia (SLO), Hungary (H), Romania (RO), Slovakia (SK), and the Czech Republic (CZ) (see Figure 5.1) [255]. Each terminal is equipped to handle the efficient coordination between various stakeholders in the logistics chain, such as loading agents, forwarders, operators, rail transport companies, and shipping companies [255, 256, 257].

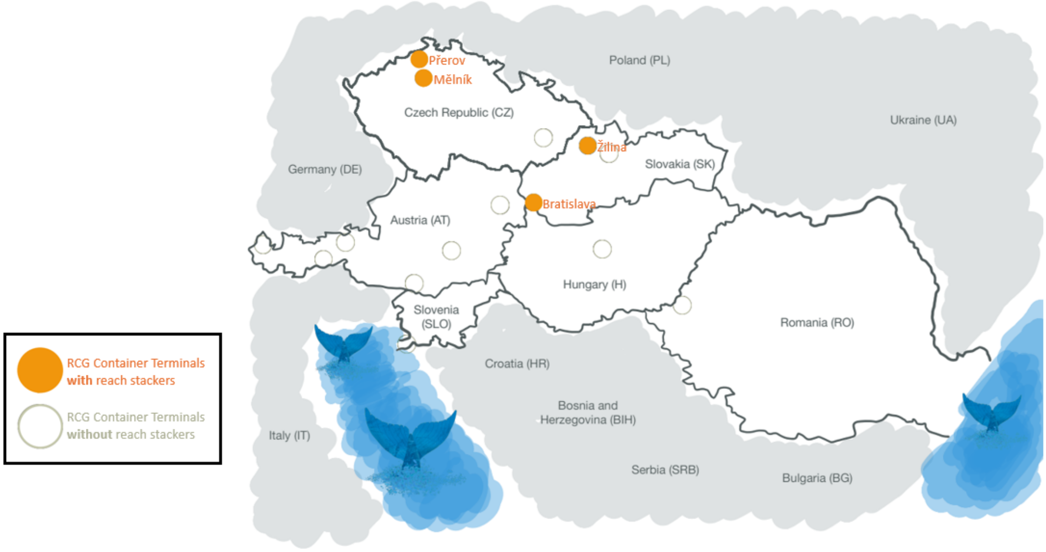

FIGURE 5.1: Location of all 15 Rail Cargo Group (RCG) container terminals, either with reach stackers (in orange) at Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK), or without reach stackers (in gray).

FIGURE 5.2: Terminal equipment for lifting and moving containers: forklift trucks, gantry cranes, and reach stackers (*left to right*).

All of the 15 RCG container terminals contain various types of equipment used for handling containers in their respective ports and intermodal yards. The types of equipment used for lifting and moving containers are forklift trucks, gantry cranes, and reach stackers, depicted in Figure 5.2. While forklift trucks are known for their maneuverability, allowing for operations in tight spaces, and their versatility in attachments, they only have a lifting capacity ranging from a few thousand pounds to around 50,000 pounds. This capacity falls short for heavier industrial tasks, where gantry cranes come into play. These overhead cranes consist of a bridge supported by two or more legs running along a rail at ground level, allowing for the lift of loads up to several hundred tons. Since their mobility is limited to a predefined path, their operational flexibility, especially in dynamic environments where the layout or operations need may change, is restricted. Reach stackers, on the other hand, offer superior mobility and flexibility. They can move freely around a terminal, handle containers in tight spaces, and quickly adapt to changing operational requirements. This makes them particularly useful in environments where space is at a premium or where container stacks are not aligned in straight rows. Also, reach stackers can quickly pick up, move, and stack containers with a high degree of efficiency. Their ability to rapidly reposition containers makes them ideal for fast-paced operations,

Country	Amount of Container Terminals	Terminal Descriptions	RCG Reach Stacker Availability
AT	6	ÖBB operated	-
SLO	1	Connects SE-Europe with Far East. Import- and export-oriented	-
H	1	Connection between W- and SE-Europe	-
RO	1	Intermodal terminal	-
SK	3	Intermodal terminal	**5**
CZ	3	Intermodal terminal	**7**

TABLE 5.1: Overview of container terminals operated by the Rail Cargo Group (RCG) in Austria (AT), Slovenia (SLO), Hungary (H), Romania (RO), Slovakia (SK), and the Czech Republic (CZ), detailing a description of terminals and the availability of RCG reach stackers in each country.

such as in RCG rail yards.

A detailed description of the amount of RCG container terminals available in each of the six operational countries can be seen in Table 5.1 The six container terminals in Austria are not operated through RCG, but through the Austrian Federal Railways' infrastructure division (i.e., ÖBB). They are serving as pivotal points for the handling of containers, swap bodies, and semi-trailers. Since RCG does not operate these container terminals, there are no reach stackers to be considered (see Table 5.1) [256].

The terminal at the Port of Koper (SLO) links Central and South-Eastern Europe with the Far East. As the northernmost port of the Adriatic Sea, it serves as the primary overseas gateway to the Far East [256]. The terminal focuses on both imports and exports. It does not utilize RCG reach stackers but operates with gantry cranes (see Figure 5.2 and Table 5.1).

The Budapest BILK (**B**udapesti **I**ntermodális **L**ogisztikai **K**özpont, translated: *'Budapest Intermodal Logistics Center'*) terminal is a cornerstone of RCG's operations in Hungary. It stands as the primary handling center for unaccompanied combined transport units in the country, making it a crucial hub for combined goods transport directed towards Western and South-Eastern Europe. Similarly to the Port of Koper (SLO), no RCG reach stackers are being utilized, only gantry cranes (see Table 5.1) [256].

The Railport Arad Intermodal Terminal in Curtici (RO) is recognized as one of the largest and most modern railway terminals in the country and is among the most significant in Central and Eastern Europe, as well as the Commonwealth of Independent States (CIS). It is not being operated by RCG reach stackers, but by forklift trucks and gantry cranes (see Figure 5.2) [256].

RCG operates three key container terminals in Slovakia, located in Bratislava, Žilina, and Ružomberok, with the latter lacking any reach stackers. The terminal in Žilina, situated in the north of Central Slovakia, is crucial for the automotive industry. It focuses on trains to Kaliningrad in Russia and maintains a regular connection to the Port of Koper in Slovenia [256]. The Žilina terminal is equipped with two container reach stackers, facilitating the handling and transportation of containers on a terminal area of approximately 25,000 m². The Bratislava Terminal is strategically positioned for freight transport to Austria and Hungary. Its direct connection to the Danube enhances the efficiency of transshipment between rail and inland waterway transport. The Bratislava terminal is equipped with three container reach stackers and covers an area of more than 45,000 m². Overall, the container terminals in Slovakia have five RCG reach stackers distributed over two out of three locations (see Table 5.1)

RCG operates three key container terminals in the Czech Republic: Brno, Mělník, and Přerov. The Brno terminal is a significant hub for combined goods transport, driven by high demand. It does, however, not utilize RCG reach stackers but features three 300-meter railway sidings and two gantry cranes for the transshipment of containers, swap bodies, and semi-trailers [256]. The Mělník terminal plays a crucial role in RCG's operations, with a total area of 33,000 m². This terminal is essential for connecting the Czech Republic with German ports like Bremerhaven and Hamburg, as well as the Slovenian Port of Koper [256]. It is equipped with five RCG reach stackers, as well as gantry cranes and forklift trucks. Located in the Moravia region, the Přerov terminal is a key hub for onward connections between the Mělník-Hamburg/Bremerhaven route. It covers an area of 16,000 m² and is equipped with two RCG reach stackers for loading and unloading operations. Overall, the container terminals in the Czech Republic have a total of seven RCG reach stackers in two out of their three locations (see Table 5.1).

In total, RCG operates twelve reach stackers at their locations in Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK). A thorough analysis of these reach stackers is provided in the following subchapter.

5.2.1 RCG Reach Stacker

Reach stackers are a type of forklift that are primarily used for handling intermodal cargo containers in small terminals or medium-sized ports. They play an integral part in logistics operations, particularly in port or rail environments, as they are designed to lift (loaded) containers from trucks, trains, and vessels, maneuver them across a yard, and then stack them for storage or reload them onto another transportation vehicle [258]. The operation of reach stackers is based on principles of stability similar to a see-saw, where the weight of the load and its distance from the fulcrum (i.e., the pivot point) determine the stability of the machine [258]. The Rail Cargo Group (RCG) operates twelve reach stackers in their intermodal terminals in Mělník, Přerov, Bratislava, and Žilina, respectively (see Table 5.2) . The manufacturers are Kalmar (Models: DRF 450 70C5XS, DRF 450 60C5X, and DRF 450 60S5 in Mělník) and Hyster (Models: RS46-24 IH, RS46-33CH, and RS46-29CH in Přerov, Bratislava, and Žilina).

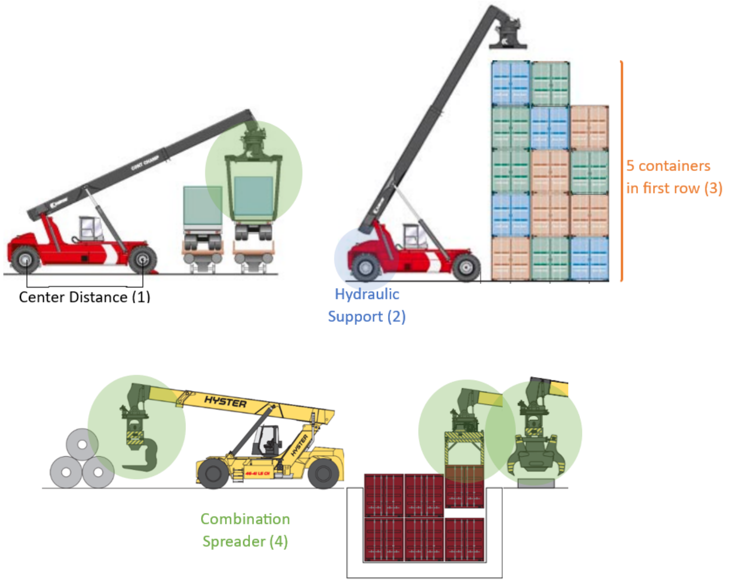

FIGURE 5.3: Technical diagram illustrating various types of cargo handling equipment and functionalities of reach stackers. Including center distance (1), hydraulic support (2), stacking capability of 5 rows of containers in the first row (3), combination spreaders for various types of cargo handling (5).

Model	*DRF 450 70C5XS*	*DRF 450 60C5X*	*DRF 450 60S5*	RS46-24 IH
Manufacturer	Kalmar	Kalmar	Kalmar	Hyster
Amount	3	1	1	2
Location	Mělník (CZ)	Mělník (CZ)	Mělník (CZ)	Přerov (CZ)
Fuel Type	Diesel	Diesel	Diesel	Diesel
Engine	Volvo TAD 1250VE			Cummins QSM11
Contract until	no data	no data	no data	2026

Model	*RS46-33CH*		*RS46-29CH*	
Manufacturer	Hyster		Hyster	
Amount	2	1	1	1
Location	Bratislava (SK)	Žilina (SK)	Bratislava (SK)	Žilina (SK)
Fuel Type	Diesel	Diesel	Diesel	Diesel
Engine	Cummins QSM11			
Contract until	no data	2026 (+ 5 years)	no data	2024 (+ 5 years)

TABLE 5.2: Detailed information about various models of reach stackers, including their manufacturers, quantities, locations, fuel types, engines, and contract duration.

Kalmar Reach Stackers: DRF 450 70C5XS, DRF 450 60C5X, and DRF 450 60S5

RCG utilizes five Kalmar reach stackers, all located in Mělník (CZ) (see Table 5.2). The type designation and their explanation of each reach stacker can be seen in Table 5.3 and Table 5.3 [259].

D	D	D	**D**iesel
R	R	R	**R**each Stacker
F	F	F	Generation
450	450	450	Load Capacity in the first row [decitons]
75	60	60	Center Distance; [decimeters]
C	C	S	**C**ombination Spreader, or **S**ingle Spreader
5	5	5	Stacking of **5** containers high in the 1st row
X	X		Additional Capacity in second to third row
S			Second Track Hydraulic Support

TABLE 5.3: Specifications and features of Kalmar reach stackers encompassed in their respective model descriptions, including load capacity, center distance, type of spreader, stacking capability, additional capacity, and the presence of a second track hydraulic support.

All DRF Kalmar reach stackers used by RCG in Mělník are equipped with diesel engines, which provide the necessary power and torque for heavy-duty applications [259, 260]. These machines belong to the 'Generation F' models, which introduced the K-Motion drivetrain system to the market. This system uses a continuously variable transmission (CVT) instead of a traditional stepped transmissions, which provides a smoother power delivery and transitions between speed [259]. The K-Motion system is also programmed to precisely match the power output to the load being handled, by sensing the weight of the load and adjusting the power accordingly, ultimately helping to reduce fuel consumption and emissions by up to 40 % compared to older reach stacker models [259].

The fourth row of Table 5.3 shows the load capacity in the first row in decitons. All three models can lift 45 tons (i.e., 450 decitons) in the first row, 5 containers high (i.e., approximately 14.4 meters high; see 7th row of 5.3 and 5.3) [261]. This equips them for lifting even the heaviest containers with a max. of around 30 tons, while utilizing the available space most efficiently and increasing the overall storage capacity at container terminals compared to previous generations [261].

The center distance between the front and rear axles varies from 60 to 75 decimeters (see 5th row in Table 5.3 and Figure 5.3). The shorter the center distance, the higher the maneuverability, due to a shorter wheelbase allowing for a tighter turning radius. Contrarily, reach stackers with larger center distances provide more stability when handling heavy loads, especially at higher lift heights, since a longer wheelbase helps distributing the weight more evenly and reduces the risk of tipping [260].

The DRF reach stackers are either equipped with a combination spreader or a single spreader system. The combination spreader can handle both containers and trailers/swap bodies without the need for additional attachments or reconfiguration (see 5.3). This versatility allows for efficient and seamless material handling operations. The single spreader, on the other hand, is dedicated solely to container handling, providing a more specialized solution. At Mělník, four out of the five Kalmar reach stackers are equipped with combination spreaders, that can also lift containers from/to the second and third row or track (see 5.3). This additional capacity is supported in three out of the four reach stackers by a hydraulic support systems, which provides additional stability.

Hyster Reach Stackers: RS46-24 IH, RS46-33CH, and RS46-29CH

Similar to the RCG Kalmar reach stackers, the ones from Hyster also differ in loading capacity, maximum lift height, and availability of hydraulics, disclosed in a unique type designation for each model [262, 263, 264].

R	R	R	**R**each Stacker
S	S	S	**S**traddle
46	46	46	Load Capacity in the first row; [tons]
24	33	29	Load Capacity in the second row; [tons]
IH	CH	CH	**I**ntermodal **H**andler, vs. **C**ontainer **H**andler

TABLE 5.4: Specifications and features of Hyster reach stackers encompassed in their respective model descriptions, including load capacity in the first and second row, and type of handler.

RCG has seven Hyster reach stackers of three models in three locations (i.e., Přerov (CZ), Bratislava (SK), and Žilina (SK)). The three distinct models share partly the same code, explained in Table 5.4. The letter ’R’ stands for reach stacker, the ’S’ for ’Straddle’ (i.e., operation occurs while sitting down), and the number ’46’ represents the loading capacity of the machine in tons. The actual loading capacity depends on the length of the container and the type of reach stacker. The ones used by RCG can lift 32 - 35 ton 20′ containers, or 14 - 16 ton 40′ containers, respectively [263]. The code then varies amongst the three Hyster models. ’24, 33, and 29’ stand for the load capacity of the second row without the use of a stabilizer, respectively.

Contrarily to the Kalmar models operated in Mělník, Hyster reach stackers do not have their center distance displayed in their code, which is 62 decimeters for all three models [263]. Similar to the Kalmar reach stackers, the ones from Hyster also account for a stacking height of five containers in the first row, resulting in 5 x 9′6″ (i.e., approximately 14.4 m) in height.

The last part of the code contains either ’IH’ or ’CH’, which stand for ’Intermodal Handler’ and ’Container Handler’, respectively. There is two reach stackers in Přerov (CZ) that are used for intermodal operations. These involve the transportation and handling of containers across different modes of transport (e.g., from rail to truck). The three and two remaining Hyster reach stackers in Bratislava and Žilina, respectively, are categorized as Container Handlers. This designation indicates that the reach stacker is primarily used for handling containers, used in ports and terminals for stacking and moving containers efficiently within the facility [264].

Key Differences and Similarities in RCG Reach Stackers

Overall, the models of the Kalmar and Hyster reach stackers have a lot of similarities, which are described in their codes, respectively. All six models are designed for heavy-duty container handling, capable of stacking up to five containers high and moving them efficiently within container terminals or intermodal facilities. Their engines are powered by diesel, which provides the necessary torque and power for lifting even the heaviest loads between 14 to 45 tons. Specifically, Kalmar reach stackers are equipped with Volvo TAD 1250VE engines, and Hyster reach stackers with Cummins QSM11 engines [265]. Both are formidable inline 6-cylinder diesel engines, engineered for demanding marine and industrial applications. The Cummins QSM11 offers a displacement of 10.8 liters and has a power range of 220 to 526 kW, at rated speeds of 1800 - 2500 rpm, with a peak torque between 1573 to 2372 Nm [266]. This engine employs a turbocharged and air-to-air aftercooled aspiration system, coupled with the Cummins Celect electronic unit injection fuel system. It meets emissions certifications for EPA Tier 2, IMO, and RCD standards. Contrarily, Volvo TAD1250VE offers a slightly larger displacement of 12.1 liters and a power output of 247 kW at 1900 rpm, with the peak torque not being specified [267]. Similar to the Cummins engine, it utilizes a turbocharged aspiration system with an air-to-air aftercooler and employs unit injectors for its fuel system. The Volvo engine adheres to more stringent emissions standards, being certified for EPA Tier 3 and EU Stage III [268]. One major difference in Kalmar and Hyster reach stackers lies in their drivetrain technology. Kalmar uses a K-Motion drivetrain system, that matches the power output precisely to the load being handled, reducing fuel consumption and emissions by up to 40 % compared to traditional models like the Hyster reach stackers employed by RCG [259]. Another variation lies in their center distance and consequent maneuverability and stability. While Kalmar offers variations in the center distance between the front and rear axles (i.e., 60 to 75 decimeters), all three models of Hyster have a fixed center distance of 62 decimeters [260, 263].

5.3 Alternative Fuels for RCG Reach Stackers

5.3.1 Overview

Rail Cargo Group (RCG) is a premier rail logistics provider in Europe, operating in 18 countries with traction companies in 13 European nations. The company is dedicated to promoting the most environmentally friendly mode of transport - railways - and is actively collaborating across Europe and with its partners to achieve a modal shift [252]. RCG manages several key container terminals across Europe, including locations in Slovakia (Bratislava and Žilina) and the Czech Republic (Mělník and Přerov). These terminals serve as crucial hubs for freight transport between Eastern and Western Europe [256]. A primary piece of equipment used in these container terminals is the reach stacker, which has traditionally been powered by conventional diesel engines and is thoroughly analyzed in the chapter 5.2.1. In line with RCG's commitment to sustainable transport, the company is exploring the adoption of alternative fuels for their reach stackers. This initiative aligns with their broader environmental strategy [254]. To ensure the suitability of alternative fuels for their specific engine types and industrial requirements, a comprehensive evaluation will be conducted to determine the efficiency and performance metrics of previously assessed alternative fuels: hydrogen, biodiesel, and synthetic fuels (particularly e-fuels).

5.3.2 Hydrogen for RCG Reach Stackers

Hydrogen Infrastructure in the Czech Republic (CZ) and Slovakia (SK)

The current state of hydrogen infrastructure in the Czech Republic (CZ) and Slovakia (SK) reflects a burgeoning yet nascent sector, driven by ambitious national strategies and plans. In the Czech Republic, the National Action Plan for Clean Mobility (NAP CM) underscores the government's commitment to integrating hydrogen into the transportation sector, with specific targets to deploy 95 hydrogen buses by 2025 and 870 by 2030 [269]. The plan also aims to establish approximately 80 hydrogen fueling stations by 2030, although this target is considered optimistic given the current pace of development, with only one operational station and nine more under construction [270]. In Slovakia, the National Hydrogen Strategy, adopted in June 2021, outlines a comprehensive framework for hydrogen use across various sectors, including transportation. Slovakia's infrastructure is still in its early stages, with only one permanent hydrogen filling station in Bratislava [271]. Both countries are actively pursuing hydrogen projects, but the Czech Republic appears to be slightly ahead in terms of specific targets and ongoing projects, while Slovakia is focusing on foundational infrastructure and legislative frameworks to support future growth.

Green, Pink, Blue, and Turquoise Hydrogen in the Czech Republic (CZ) and Slovakia (SK) Having identified green, pink, blue, and turquoise hydrogen as low-emitting and sustainable production methods in chapter 4.2, it is assessed, whether these types of hydrogen are available in the Czech Republic (CZ) and Slovakia (SK). This assessment is essential given that the majority of hydrogen is currently produced with significant greenhouse gas emissions, as discussed in chapter 4.2. The Czech Republic is actively pursuing green hydrogen projects, although current production remains limited. For instance, UNIPETROL plans to open a water electrolysis plant in Litvínov by 2025, targeting the production of 990 tons of green hydrogen annually using electricity from a 52 MW solar power plant. This initiative represents a significant step towards sustainable hydrogen production in the country [269]. In contrast, Slovakia is still in the very early stages of developing green hydrogen projects. The country has yet to establish substantial infrastructure or projects dedicated to green hydrogen production [271]. Given the significant share of nuclear power in the energy mix for generating electricity in both the CZ and SK (i.e., 37 % and 60 %, respectively), pink hydrogen production using nuclear plants is a viable option, that is being actively considered [272, 273]. Additionally, both countries also aim to gradually increase the use of blue and turquoise hydrogen, as they are seen as transitional solutions to decarbonize the existing hydrogen infrastructure. However, the production of these types of hydrogen is currently limited by technological and economic factors [274]. Concerning the local production capabilities, CZ and SK both face limitations, that will need to be compensated by import of low-carbon hydrogen via pipelines from abroad [274]. The Czech transmission system operator, NET4GAS, operates about 4,000 km of gas pipelines, which are expected to transport hydrogen and other renewable or decarbonized gases in the future [274]. NET4GAS is involved in planning future European infrastructure within the European Hydrogen Backbone project. Given their geographic location in the center of the EU, both countries are poised to remain an important transit state in the hydrogen transmission system, that can transport hydrogen from the east (e.g., from Ukraine via Slovakia), the south (e.g., from North Africa via Italy and Austria), and the north-west (e.g., from Germany) [274].

Overall, the Czech Republic is making strides in green hydrogen production, while Slovakia is still in the nascent stages of developing its green hydrogen infrastructure. Both countries are exploring pink hydrogen production due to their significant nuclear energy capacities and are considering blue and turquoise hydrogen as transitional solutions. However, local production limitations necessitate the import of low-carbon hydrogen, leveraging their strategic positions within the European hydrogen transmission network. The predominant method of hydrogen production remains gray hydrogen, which is linked to significant greenhouse gas emissions, as discussed in chapter 4.2.

Modifications Required for Diesel Engines to Run on Hydrogen

The reach stackers operated by the Rail Cargo Group (RCG) are all diesel powered (see Table 5.2). To harness the potential of hydrogen as a clean fuel alternative, these engines must undergo significant modifications to ensure efficient and safe operation. Diesel engines are compression ignition engines that rely on the high temperature resulting from compressing air to ignite the injected diesel fuel. The fuel is injected directly into the combustion chamber towards the end of the compression stroke, where it ignites due to the high temperature of the compressed air.

For a conventional diesel engine to (partly) run on hydrogen, it can either be equipped with a port injection system, a direct injection system into the cylinder, or a dual-mode operation system, where the existing diesel fuel injection systems is retained but modified to inject a diesel-hydrogen blend [1] [275, 276, 277]. Additionally, the air intake system must be redesigned and optimized to improve the volumetric efficiency for the hydrogen-air mixture [278]. Also, the cylinder head and combustion chamber geometry must be modified to enable controlled ignition of the hydrogen-air mixture, which has different combustion characteristics than diesel fuel [278, 279]. And new engine control strategies and calibrations for dual-fuel or hydrogen-only operation must be developed, including the injection timing, quantity, and air-fuel ratios [276, 277].

Overall the extent of modifications depends on whether the engine will operate in dual-fuel mode or solely on hydrogen. Dual-fuel operation generally requires fewer modifications compared to a dedicated hydrogen engine [277].

The same hold for the costs associated with converting a conventional diesel engine. Should the fuel injection system be a dual-fuel mode, the total costs typically range from $3,000 to $7,500, depending on engine size, complexity, and the specific components used [280, 281, 282]. Converting a diesel engine to run exclusively on hydrogen requires more extensive modifications and higher costs, ranging from $20,000 to $50,000 or more [278, 283].

Evaluation of Suitability

Utilizing hydrogen as an alternative fuel for reach stackers has the potential to substantially reduce the carbon footprint of RCG's industrial operations. This initiative aligns seamlessly with the company's global sustainability objectives and could simultaneously enhance its corporate image and market competitiveness.

But despite its potential, the current state of hydrogen technology and infrastructure in the Czech Republic (CZ) and Slovakia (SK) presents several weaknesses, which dampens the enthusiasm for modifying the current diesel-powered RCG reach stackers in Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK). The predominant use of gray hydrogen, which is produced from fossil fuels, undermines the environmental benefits of transitioning to hydrogen-powered reach stackers. This method is associated with high greenhouse gas emissions and a reliance on energy supplies from politically unstable regions, as detailed in subchapter 2.2 and chapter 4.2. Furthermore, the share of renewable energy in these countries is below the EU average, making the production of low-emission and sustainable hydrogen, particularly green hydrogen, challenging. The high capital expenditure required for hydrogen infrastructure and the current economic disadvantage of clean hydrogen compared to other alternatives pose significant financial risks. Additionally, the storage and transport challenges associated with low-emission and sustainable hydrogen further complicate the transition.

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[1] In a dual-fuel mode the hydrogen is introduced into the engine along with a small amount of diesel fuel as a pilot ignition source

However, hydrogen shows significant opportunities associated with the future adoption as an alternative fuel for RCG reach stackers. A key indicator of readiness for this transition would be the chemical industry's shift from gray to green, pink, blue, or turquoise hydrogen. This industry, which already uses hydrogen extensively for ammonia production and oil refining, is at the forefront of pushing this transition in the Czech Republic (CZ) and Slovakia (SK). Once the storage and transport challenges are resolved, and the infrastructure and technology have advanced further, it would be advisable to consider modifying RCG reach stackers to be made suitable for hydrogen-powered engines. By negotiating new contracts with manufacturers Hyster and Kalmar, wherein part of the modification costs are covered by these companies, RCG could make the transition economically more viable. This strategic move could also open up new funding opportunities and partnerships aimed at promoting sustainable industrial practices.

Also, there might be the future possibility for RCG to contract hydrogen-powered reach stackers by Hyster that are not powered by modified diesel engines, but by hydrogen fuel cells that generate electricity through an electrochemical reaction between hydrogen and oxygen. These reach stackers are currently being tested as part of the 'H2PORTS' project in Valencia, Spain, and offer performance metrics comparable to those of traditional diesel-powered reach stackers [284]. Specifically, they match diesel trucks in terms of capacity, lift speeds, and driving speeds, thereby supporting similar productivity levels. The hydrogen reach stacker features independent traction and hydraulic systems, each driven by separate electric motors tailored for specific functions. This design ensures efficient and reliable operation. The reach stacker can operate for up to one day on a single hydrogen refill, which is a critical factor for maintaining operational continuity in busy terminal environments. A key component of the H2PORTS project is the development of a mobile Hydrogen Refueling Station (HRS) by CNH2, which provides flexibility and convenience, facilitating the integration of hydrogen-powered equipment into existing terminal operations without significant infrastructure modifications.

Therefore, given the current state of hydrogen technology and infrastructure in the Czech Republic (CZ) and Slovakia (SK), it is premature to transition RCG's diesel-powered reach stackers to hydrogen. Once the contracts for the existing reach stackers expire, it would be prudent to consider Hyster reach stackers powered by hydrogen fuel cells, dependent upon the results of the H2PORTS project in Valencia, Spain.

5.3.3 Biofuels for RCG Reach Stackers

Biofuel Availability and Infrastructure

The regulatory framework for biofuels in the Czech Republic (CZ) and Slovakia (SK) is shaped by a combination of national legislation and EU directives aimed at promoting renewable energy and reducing greenhouse gas emissions. In the Czech

Republic, biofuels are supported through tax exemptions and mandatory blending quotas, as outlined in the Air Protection Act and the Act on Consumption Taxes [285]. Similarly, Slovakia mandates biofuel blending, requiring motor gasoline to contain at least 9 % bioethanol and diesel to include 6.9 % biodiesel, as per Act No. 309/2009 Coll. [286, 287]. Both countries have set ambitious targets for biofuel adoption, with the Czech Republic aiming to increase the share of renewable energy in transport to 14 % by 2030 [269] , while Slovakia is working towards compliance with EU sustainability criteria and greenhouse gas reduction targets [286].

In terms of biofuel availability and infrastructure, the Czech Republic boasts several production facilities, including biodiesel plants with a combined capacity of over 400,000 metric tons per year and bioethanol plants capable of producing nearly 300,000 metric tons annually [288]. Slovakia also has significant production capabilities, with facilities like the 55,000 metric ton cellulosic ethanol plant in Strazske [288, 289]. Feedstock availability in both countries is robust, with the Czech Republic leveraging rapeseed for biodiesel and sugar beet and corn for bioethanol, while Slovakia focuses on non-food biomass for biofuel production [288]. Distribution and fueling infrastructure are well-developed, with biofuels being integrated into conventional fuel supply chains, allowing for immediate market entry without the need for separate infrastructure [290].

Evaluation of Suitability

Biofuels are being actively pursued and subsidized in both the Czech Republic (CZ) and Slovakia (SK), making them, especially biodiesel, promising alternatives for the diesel-powered reach stackers in Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK). However, the approach to biofuel production in these two countries differs, leading to distinct advantages and disadvantages.

The Czech Republic primarily produces first-generation biofuels, such as biodiesel from rapeseed oil and bioethanol from sugar beet and corn. While these biofuels offer an alternative to fossil fuels, they are associated with several environmental issues, as discussed in detail in subchapter 4.3.2. These issues include deforestation, loss of biodiversity, water pollution, eutrophication, and changes in land use. Given these concerns, the use of first-generation biodiesel in the Czech Republic for RCG reach stackers is not advisable. The environmental costs outweigh the benefits, and the sustainability of these biofuels is questionable.

Biofuels are being actively pursued and subsidized in both the Czech Republic (CZ) and Slovakia (SK). This makes them, especially biodiesel, promising alternatives for the diesel-powered reach stackers in in Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK). However, the CZ primarily produces first generation biofuels, such as biodiesel from rapeseed oil and bioethanol from sugar beet and corn. These biofuels are associated with several environmental issues, such as deforestation, loss of biodiversity, water pollution, eutrophication, and changes in land use, as explained in great detail in subchapter Given these issues, the use of first generation biodiesel in the CZ is not advisable for RCG reach stackers. The environmental costs outweigh the benefits, and the sustainability of these biofuels is questionable.

In contrast, Slovakia focuses on producing biofuels from non-food biomass, which is considered more sustainable, as described in detail in subchapter 4.3.3. The primary product is cellulosic ethanol, produced from agricultural residues and forestry by-products. This approach avoids competition with food crops and reduces the pressure on arable land. Nevertheless, the reliance on bioethanol as the primary biofuel product in Slovakia necessitates the adoption of an unconventional ethanol-diesel blend for the reach stackers, a decision that is not without its merits and drawbacks. While these blends undoubtedly offer the advantage of reducing particulate emissions through more complete combustion and an overall improved combustion efficiency, several drawbacks temper the initial enthusiasm. This requirement introduces a unique set of challenges:

1. **Lower Calorific Value**: Bioethanol has a lower calorific value compared to diesel, which can result in reduced engine power and torque.
2. **Increased NOx Emissions**: The use of bioethanol-diesel blends can lead to an increase in nitrogen oxides (NOx) emissions, which are harmful pollutants and pose regulatory challenges.
3. **Lower Flash Point**: The lower flash point of bioethanol-diesel blends compared to pure diesel poses risks in storage and handling, requiring special precautions to prevent fire hazards.
4. **Phase Separation**: Bioethanol is immiscible with diesel over a wide range of temperatures and in the presence of water, leading to phase separation. This necessitates the use of surfactants or cosolvents to maintain blend stability, which can complicate fuel formulation and increase costs. This aspect is explained further in the following.

A study by Lapuerta et al. [291] demonstrates that diesel engines can accommodate blends with bioethanol contents up to 10 % v/v in regions where winter temperatures rarely fall below -5 °C, provided that water contamination is meticulously managed. Blends with 7 % v/v bioethanol, which are commercially viable, can even be used in colder climates. In Bratislava (SK), average low temperatures hover around -3°C, with occasional dips to -15 °C, while in Žilina (SK), the average low temperature is approximately -7 °C. January and February frequently see temperatures dropping below -5 °C. Consequently, it is imperative to further investigate the degree of phase separation between ethanol and diesel at these low temperatures and determine an appropriate blending ratio based on the extent of phase separation and temperature. Adjusting the blending ratio according to seasonal temperature variations could be a viable strategy, with reduced or no bioethanol usage during the cold winter months and an increased proportion of bioethanol during warmer months when phase separation is less problematic.

In conclusion, while both the Czech Republic (CZ) and Slovakia (SK) are committed to advancing biofuels, their strategies diverge significantly. The Czech Republic's reliance on first generation biofuels raises substantial sustainability concerns and it is therefore not recommended to consider biofuels for the usage in reach stackers operated in Mělník (CZ), Přerov (CZ). In contrast, Slovakia's focus on second generation biofuels derived from non-food biomass appears more promising. However, the implementation of bioethanol-diesel blends in Slovakia is not without its challenges. Issues such as lower calorific value, increased NOx emissions, lower flash point, and phase separation must be meticulously addressed to ensure the successful deployment of these biofuels in reach stackers operated in Bratislava (SK), and Žilina (SK).

5.3.4 Synthetic Fuels for RCG Reach Stackers

E-Diesel Infrastructure in the Czech Republic (CZ) and Slovakia (SK)

Synthetic diesel, specifically e-diesel, produced through processes like Fischer-Tropsch synthesis are known for their high purity, consistent quality, sustainability, and chemical similarity to conventional diesel (*see subchapter 4.4 for a more detailed analysis*). These characteristics qualify e-diesel as an alternative fuel for diesel-powered RCG reach stackers in Mělník (CZ), Přerov (CZ), Bratislava (SK), and Žilina (SK).

Both the Czech Republic (CZ) and Slovakia (SK) are actively developing a synthetic diesel infrastructure. However, the production processes of these endeavors are not necessarily limiting environmental degradation as assessed in subchapter 4.4. In the Czech Republic (CZ), the focus of hydrogen production is shifting from gray to sustainable forms of green, pink, blue, and turquoise hydrogen. Despite these efforts, there are no operational projects or commercial production of e-diesel from these types of hydrogen and captured carbon dioxide currently listed in the country. Additionally, the Czech Republic's hydrogen strategy acknowledges the need for hydrogen imports due to limited domestic renewable energy resources, which further complicates the immediate adoption of e-diesel. Similarly, Slovakia is in the early stages of developing its hydrogen infrastructure as explained in paragraph 5.3.2. The Slovak government has adopted a National Hydrogen Strategy aimed at increasing the competitiveness of the Slovak economy and contributing to a carbon-neutral society. This strategy includes the potential for hydrogen injection into the natural gas grid and the use of nuclear energy to produce low-carbon hydrogen. However, like the Czech Republic, Slovakia does not yet have operational projects or commercial production of e-diesel from sustainable hydrogen and captured CO2.

In those countries, there are no operational projects or commercial production of e-diesel from green, pink, blue, or turquoise hydrogen and captured carbon dioxide currently listed in those countries.

Evaluating the Suitability

The production pathways of synthetic diesel from sustainable hydrogen (i.e., green, pink, blue, and turquoise) and captured CO2 are identified as the least environmentally damaging in subchapter 4.4. This type of synthetic diesel, referred to as e-diesel, offers a promising alternative to traditional fossil fuels due to its potential to significantly reduce greenhouse gas emissions. However, the current state of production infrastructure in the Czech Republic (CZ) and Slovakia (SK) does not support the widespread adoption of e-diesel. Therefore, it is not recommended to utilize synthetic diesel at this stage in either country.

Instead, it is advisable to wait for the chemical industry's shift from gray hydrogen, which is currently predominant, to more sustainable forms such as green, pink, blue, or turquoise hydrogen, as explained in paragraph 5.3.2. The chemical industry in CZ and SK, which already uses hydrogen extensively for ammonia production and oil refining, is at the forefront of pushing this transition. This shift is crucial as it will lay the groundwork for the broader adoption of e-diesel and other synthetic fuels.

Once the chemical industry in CZ and SK has successfully transitioned to using sustainable hydrogen, it will create a more favorable environment for the production and utilization of e-diesel. At this point, the Rail Cargo Group (RCG) is recommended to actively participate in this transition by offering itself up for pilot projects to test out e-diesel. By doing so, RCG can play a pivotal role in demonstrating the viability and benefits of e-diesel, thereby accelerating its adoption in the transport sector.

In conclusion, while e-diesel presents a great alternative fuel option, its current feasibility in CZ and SK is limited by the lack of production pathways and infrastructure. The focus should be on supporting the chemical industry's shift to sustainable hydrogen, which will pave the way for the future use of e-diesel. RCG's involvement in pilot projects will be instrumental in this transition, showcasing the potential of e-diesel and contributing to the broader goal of reducing carbon emissions in the transport sector.

5.3.5 Outlook

Reach stackers play a crucial role in the logistics and intermodal transport sectors, particularly in handling containers at ports, terminals, and rail yards. The Rail Cargo Group (RCG) operates several key terminals in Central Europe, including Mělník and Přerov in the Czech Republic, and Bratislava and Žilina in Slovakia. The future of reach stackers is driven by environmental concerns, that has shifted their development and research toward electric engines, that offer several advantages, including environmental benefits, operational efficiency, and reduced maintenance costs. Kalmar, which provides five reach stackers in Mělník (CZ) is at the forefront of developing electric reach stackers with lifting capacities up to 45 tonnes, designed to improve eco-efficiency and reduce carbon emissions. These machines use modular battery options and advanced charging solutions to meet diverse operational needs. They are also using SSAB Green Steel and biodegradable hydraulic oils, which significantly reduce the embedded carbon in the manufacturing process, making Kalmar's reach stackers some of the most sustainable on the market. Additionally, Kalmar is integrating advanced telematics systems to enable remote monitoring, predictive maintenance, and real-time data analysis, enhancing operational efficiency and reducing downtime. Hyster, which is providing seven reach stackers in Přerov (CZ), Bratislava (SK) and Žilina (SK), is also making significant strides in developing eco-friendly and technologically advanced reach stackers. The company has developed hydrogen fuel cell reach stackers as part of the H2Ports project, offering zero emissions and quick refueling times, making them a viable alternative to diesel-powered reach stackers. Hyster is focusing on integrating automation and advanced safety features into its reach stackers, including the use of sensors, 3D cameras, and driver-assistance systems to enhance operational safety and efficiency. The company is actively involved in collaborative projects aimed at developing next-generation hydrogen-powered port equipment, contributing to broader efforts to achieve climate neutrality and reduce emissions in port operations.

The future of reach stackers, particularly those operated by the Rail Cargo Group in Central Europe, is poised for significant advancements driven by sustainability and technological innovation. The transition to electric and hydrogen fuel cell-powered reach stackers offers substantial environmental and operational benefits. Continued research into battery technology, hydrogen fuel cells, infrastructure development, and automation will be crucial in realizing the full potential of these machines.

Chapter 6

Conclusion

The reliance on fossil fuels has posed significant challenges, including resource depletion, energy insecurity, and environmental degradation, particularly through greenhouse gas emissions and climate change. Addressing these issues necessitates a transition towards sustainable and renewable alternative fuels. This thesis has comprehensively evaluated the potential of hydrogen, biofuels, and synthetic fuels as viable alternatives to fossil fuels, with a specific focus on their application in the operations of Rail Cargo Group (RCG) reach stackers at four European locations. A concise overview of key factors influencing the feasibility and environmental impact of these alternative fuels is depicted in Table 6.1 and explained in the following.

Hydrogen emerges as a promising alternative fuel, offering a carbon-free energy carrier when produced through low-emission methods such as electrolysis using renewable or nuclear energy (green and pink hydrogen), steam methane reforming with carbon capture and storage (blue hydrogen), and methane pyrolysis (turquoise hydrogen). While green and pink hydrogen have minimal carbon footprints, their high production costs currently hinder widespread adoption. Blue hydrogen presents a more economically viable option, contingent on the effectiveness of carbon capture and storage technologies. Turquoise hydrogen shows potential for solid carbon utilization but requires further technological advancements. Hydrogen storage and transportation methods involve trade-offs between energy density, cost, and safety considerations.

Biofuels offer a diverse range of options, categorized into first, second, and third generations. First-generation biofuels, derived from food crops like corn and soybeans, have raised concerns about food security and indirect land-use changes. Second-generation biofuels, produced from non-food biomass such as agricultural residues and dedicated energy crops, address some of these issues but face technological and economic challenges. Third-generation biofuels from algal biomass hold significant promise due to their high productivity and minimal land-use impact, but their commercialization is hindered by high production costs and technological barriers.

Synthetic fuels, particularly e-fuels produced from captured carbon dioxide and water using renewable or decarbonized electricity, have garnered attention for their potential to mitigate climate change. Power-to-Gas (PtG) technologies can produce e-hydrogen and e-methane, while Power-to-Liquid (PtL) processes yield e-methanol,

	Strenghts	**Weaknesses**	**Opportunities**
Hydrogen	Zero direct emissions, high energy density, versatile applications	High production cost, limited infrastructure, storage + transport challenges	Declining costs of renewable energy, advancements in production and storage technologies, growing policy support
Biofuels	Potentially carbon-neutral, existing infrastructure, support agricultural economies	Land use conflicts, water-intensive production, potential food vs. fuel trade-offs, technological readiness	Development of advanced biofuels from non-food feedstocks, improved conversion efficiencies, supportive policies
Synthetic Fuels	Existing infrastructure, potentially carbon-neutral, scalability	Energy-intensive production, reliance on carbon capture technologies, high costs	Potential for negative emissions, integration with renewable energy sources, compatability with existing infrastructure

TABLE 6.1: Concise overview of key factors influencing the feasibility and environmental impact of hydrogen, biofuels, and synthetic fuels as potential replacements for fossil fuels. Categorized into 'Strengths', 'Weaknesses', and 'Opportunities'.

e-diesel, e-kerosene, and e-gasoline. These e-fuels offer compatibility with existing infrastructure and the possibility of achieving carbon neutrality or even negativity.

The case study on RCG reach stackers highlighted the feasibility and challenges of integrating alternative fuels into existing operations. While hydrogen and e-diesel present viable options, their adoption is contingent on the development of supporting infrastructure and technological advancements to ensure cost-effectiveness and operational compatibility.

Overall, the transition from fossil fuels to alternative fuels is a complex endeavor that requires a multifaceted approach. No single alternative fuel emerges as a universal solution, and a combination of different options may be necessary to meet diverse energy needs while minimizing environmental impact. Continued research, technological innovation, supportive policies, and strategic investments are crucial to overcome the economic and technological barriers hindering the widespread adoption of alternative fuels.

As the world grapples with the pressing challenges of climate change and energy security, the findings of this thesis underscore the urgency of accelerating the transition towards sustainable energy sources. By embracing alternative fuels and fostering a collaborative approach among stakeholders, we can pave the way for a more sustainable and resilient energy future.

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List of Abbreviations

AD	Anaerobic Digestion
AFI	Alternative Fuel Initiative
AT	Austria
CAPEX	Capital Expenditure
CBA	Cost Benefit Analyses
CCS	Carbon Capture Storage
CCU	Carbon Capture Utilization
CCUS	Carbon Capture Utilization Storage
CFC	Chlorofluorocarbon
$\mathbf{CH_4}$	Methane
CNG	Compressed Natural Gas
$\mathbf{CO_2}$	Carbon Dioxide
CVT	Continuously Variable Transmission
CZ	Czech Republic
DEC	Dedicated Energy Crop
DLUC	Direct Land Use Change
EC	European Commission
EU	European Union
ESLEM	European Strategy for Low-Emission Mobility
FCEV	Fuel Cell Electric Vehicle
FTS	Fischer-Tropsch Synthesis
GHG	Greenhouse Gas
GWP	Global Warming Potential
H	Hungary
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
$\mathbf{H_2O}$	Water
IBC	Intermediate Bioenergy Carrier
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life-cycle Assessment
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas

NH_3	Ammonia
NZE	Net Zero Emissions
N_2O	Nitrous Oxide
ÖBB	Österreichische Bundesbahn (engl: Austrian Federal Railways)
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operational Expenditure
O_2	Oxygen
PEM	Proton Exchange Membrane
PFC	Perfluorocarbon
ppm	Parts per Million
ppt	Parts per Trillion
PtG	Power-to-Gas
PtL	Power-to-Liquid
PV	Photovoltaic
RCG	Rail Cargo Group
RO	Romania
RWGS	Reverse Water Gas Shift
SF_6	Sulfur hexafluoride
SK	Slovakia
SLO	Slovenia
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyzer Cell
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WGS	Water Gas Shift

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