Chair of Energy Network Technology

Master's Thesis

REQUIREMENTS FOR THE ENERGY-OPTIMAL TRANSFORMATION OF THE EUROPEAN ENERGY SYSTEM

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June 2023

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created on

Chair of Energy Network Technology

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FOREWORD

I would like to use this opportunity to thank first of all my family for providing me the possibility to start my studies abroad, for supporting my initiatives, and for motivating me to keep pushing through the hard exam periods mostly the first and second semesters of my bachelor's degree and for the believing in my powers and my capabilities. Without my family, none of my achievements would be possible and will make no sense.

A big thank you goes to the Federal Republic of Austria for letting foreign students come here and be taught by the best professors and lecturers in the world. Also, a big thank you to the city of Leoben for the possibilities presented over the last six years. I want to thank the Monta University Leoben for accepting my documents back in July of 2017 and for mentoring me thorough out all this time, for exchanging valuable information with me, for the opportunity to receive more than once the Leistungsstipendium, for the challenges and sleepless nights which build up my stainless steel character, for the constructive critic received and for always being friendly and being the place where I will always feel like home. Finally, I want to thank my study coordinator Frau Doris Winter for the for the excellent support during my studies.

I would like to thank the Chair of Electrical Engineering, namely the em.O.Univ.-Prof. Dipl.-Ing. Dr.techn. Helmut Weiß, Dr.mont. Dipl.-Ing. Schmid Andreas. Dipl.-Ing. Thomas Winkler and Fitzko Janina for the wonderful time we spent together discussing different interesting topics while enjoying coffee, for the opportunity to work part-time, for mentoring me through my bachelor's Thesis, and for the memories which will remain always with me.I would like to thank the Chair of Energy Network Technology, namely the head of the Chair of the Univ.-Prof. Dipl.-Ing. Dr.techn. Thomas Kienberger for the opportunity to write my master's Thesis here. A big thank you goes to my mentor Dipl.-Ing. Peter Nagovnak for choosing me as the one who will research the future energy system of the EU in 2050, for his patience while answering my question, for always making time to meet with me, for sharing his experience and ideas about different topics, for always being positive and telling his opinions, for his constructive and qualitative inputs during my work and thanks for meeting you.

A big thank you goes to my girlfriend Anna Kuzmenko for supporting me in any possible aspects and in any possible way, for sharing your point of view, which in most cases was right, for being near me even when I did not ask for, for teaching me skills which I never thought about and simply for the fact that you are with me. At this point, I would like to thank all my colleagues for the reciprocal help during these studies, for the professional discussions for unforgettable nights and memories gathered, and for the opportunity to create friendships that will last even after I finish my studies. Finally, I want to thank myself for pushing it till the

end, for always being myself, for being courageous, and for leaving a good image of my country, the Republic of Moldova.

Abstract

The European Union aims to assume a global leadership role in transforming the energy system towards climate neutrality. To achieve this objective, the EU has developed a comprehensive plan that all member states must follow. This guidance is provided by the European Green Deal. To manage the transition from fossil fuels towards Renewable energy sources (RES) an increase in the installation of the RES must be made as well as improvements in the applied technologies must occur. This thesis analysis the current energy system using an exergy-based approach. Therefore, is possible to determine the best technological portfolio in order to increase the efficiency of the entire system. This work analysis the supply-side, namely the power generation from RES as well as the final exergy application for different technologies. It also considers two different scenarios for the supply side. The first scenario represents a constant evolution of renewable energy sources, and the second scenario represents a progressive development. The methodology describes the steps done in order to determine the useful exergy demand for different technologies. The optimization environment oemof together with a greenfield approach enabled the representation of the future exergy system of the EU in 2050.

The results of this work indicate that to achieve the stated goals by the EU a progressive approach in the installation of RES must be implemented. Moreover, climate neutrality will be achieved if renewable gases are produced or used. The results show that the future energy system is highly dependent on gas imports. The amount of gas imported doubled compared to 2019 reaching 8294 TWh per year. The highest impact on the overall efficiency is given by the transport sector (26 %) as well as the process heat supply at high temperatures (32 %). The reason is the increased heat utilization and the application of heat pumps. On the other side, in the transport sector is the usage of electric vehicles and fuel cells. From an exergetic point of view, the excess electricity due to the residual loads is utilized to charge the Batterie electric vehicles (BEV) as well as to produce H_2 via electrolysis. On the other hand, the massive expansion of heat pumps also increases the efficiency of the system. The heat pump demands less electricity to increase the operating temperatures. The results indicate that the future energy system consists of two central heating grids that operate at 34°C and 90°C and a decentral grid operating at 150°C Therefore, due to these grids, the implementation of energy cascades is possible which also increases the overall efficiency. Due to all these technologies, the electrification degree is raised. The results also indicate that the overall efficiency of the EU can increase by 23 - 32 % compared to the status quo.

Keywords: exergy; renewable energy sources; primary exergy consumption; European energy system; exergy-based approach; energy efficiency.

KURZFASSUNG

Die Europäische Union strebt eine weltweite Führungsrolle bei der Umgestaltung des Energiesystems in Richtung Klimaneutralität an. Um dieses Ziel zu erreichen, hat die EU einen umfassenden Plan entwickelt, dem alle Mitgliedsstaaten folgen müssen. Dieser Plan wird durch den Europäischen Green Deal vorgegeben. Um den Übergang von fossilen Brennstoffen zu erneuerbaren Energiequellen (EE) zu bewerkstelligen, muss die Installation von EE erhöht werden und es müssen Verbesserungen bei den angewandten Technologien erfolgen. In dieser Arbeit wird das derzeitige Energiesystem mit Hilfe eines exergiebasierten Ansatzes analysiert. Dadurch ist es möglich, das beste Technologieportfolio zu bestimmen, um die Effizienz des gesamten Systems zu erhöhen. In dieser Arbeit werden die Angebotsseite, d. h. die Stromerzeugung aus erneuerbaren Energien, sowie die endgültige Exergieanwendung für verschiedene Technologien analysiert. Es werden auch zwei verschiedene Szenarien für die Angebotsseite betrachtet. Das erste Szenario geht von einer konstanten Entwicklung der erneuerbaren Energiequellen aus, das zweite Szenario von einer progressiven Entwicklung. Die Methodik beschreibt die Schritte, die unternommen werden, um den nützlichen Exergiebedarf für verschiedene Technologien zu bestimmen. Die Optimierungsumgebung oemof zusammen mit einem Greenfield-Ansatz ermöglichte die Darstellung des zukünftigen Exergiesystems der EU im Jahr 2050.

Die Ergebnisse dieser Arbeit zeigen, dass zur Erreichung der erklärten Ziele der EU ein progressiver Ansatz bei der Installation von erneuerbaren Energien umgesetzt werden muss. Darüber hinaus wird die Klimaneutralität erreicht, wenn erneuerbare Gase erzeugt oder verwendet werden. Die Ergebnisse zeigen, dass das zukünftige Energiesystem in hohem Maße von Gasimporten abhängig ist. Die Menge des importierten Gases verdoppelt sich im Vergleich zu 2019 und erreicht 8294 TWh pro Jahr. Den größten Einfluss auf die Gesamteffizienz haben der Verkehrssektor (26 %) sowie die Prozesswärmeversorgung bei hohen Temperaturen (32 %). Der Grund dafür ist die verstärkte Wärmenutzung und der Einsatz von Wärmepumpen. Auf der anderen Seite steht im Verkehrssektor der Einsatz von Elektrofahrzeugen und Brennstoffzellen. Aus exergetischer Sicht wird der durch die Residuallasten entstehende Stromüberschuss zum Laden der Batterie-Elektrofahrzeuge (BEV) sowie zur H2-Produktion durch Elektrolyse genutzt. Andererseits erhöht der massive Ausbau von Wärmepumpen auch die Effizienz des Systems. Die Wärmepumpe benötigt weniger Strom, um die Betriebstemperaturen zu erhöhen. Die Ergebnisse zeigen, dass das zukünftige Energiesystem aus zwei zentralen Wärmenetzen, die bei 34°C und 90°C arbeiten, und einem dezentralen Netz, das bei 150°C arbeitet, besteht. Durch all diese Technologien wird der Elektrifizierungsgrad erhöht. Die Ergebnisse zeigen auch, dass der Gesamtwirkungsgrad in der EU im Vergleich zum Status quo um 23 bis 32 % gesteigert werden kann.

Stichworte: Exergie; erneuerbare Energieträger; Primärexergieverbrauch; europäisches Energiesystem; exergiebasierter Ansatz; Energieeffizienz.

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NOMENCLATURE

Abbreviation

BEV	Batterie Electric Vehicles
CCS	Carbon Capture and Storage
CEAP	Circular Economy Action Plan
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
Etc.	Et cetera
EU-27	The 27 European Countries
EU-27*	The 27 European Countries + Norway and Switzerland
FEC	Final Energy Consumption
FfE	Forschungsgesellschaft für Energiewirtschaft
GDP	Gross Domestic Product
GHG	Greenhouse Gas
ICT	Information and Communication Technologies
LED	Light-Emitting Diodes
LPG	Liquified Petroleum Gas
MTO	Methanol to Olefin
NH_3	Ammonia
oemof	Open Energy System Modelling Framework
PEC	Primary Energy Consumption
PES	Primary Energy Supply
SNG	Synthetic Natural Gas
UED	Useful exergy demand

Indices

Approx.	Approximately
FV	Future Value
GWh	Gigawatt Hours
i	Rate change
i.e.	In other words
km	Kilometer
ktoe	Kilotons oil equivalent
MJ	Megajoule
Mt	Megaton
Mtoe	Million tons of oil equivalent
PV	Present Value
TWh	Terawatt hours

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1 INTRODUCTION

The European Union (EU) has set an ambitious goal of becoming the leading continent in achieving zero emissions globally by 2050. To achieve this objective, the EU has developed comprehensive plans that all member states must follow. The first proposal which was agreed upon is the Fit for 55 plan, which aims to provide a coherent and balanced framework for achieving the EU's climate objectives. These objectives include ensuring a socially equitable transition, promoting, and strengthening innovation and competitiveness in EU industries while ensuring a level playing field vis-à-vis operators from third countries and reinforcing the EU's position as a global leader in the fight against climate change [1]. The second proposal in order to achieve the stated objective is the European Green Deal. The goal of these agreements is for the member states to develop national plans to achieve an economy with net-zero Greenhouse gas emissions (GHG) and promises to protect their citizens from any kind of environmental impacts or harm. This means that the well-being of the EU is the main priority [2, 3]. The European Green Deal is made up of eight points:

1. Increasing the EU's climate ambition for 2030 and 2050
2. Supplying clean, affordable, secure energy
3. Mobilizing industry for a clean and circular economy
4. Building and renovating in an energy and resource-efficient way
5. A zero pollution ambition for a toxic-free environment
6. Preserving and restoring ecosystems and biodiversity
7. Farm to Fork: a fair, healthy, and environmentally friendly food system
8. Accelerating the shift to sustainable and smart mobility

Since most of the processes and products made in the EU have a linear approach, meaning the re-use is little, steps in a more circular economy are mandatory. Therefore, the EU came up with the Circular economy action plan (CEAP). The CEAP has as a priority to develop a strategy for attaining a more environmentally sustainable and economically competitive EU. To achieve the maximum potential the CEAP was created in collaboration with economic stakeholders, consumers, citizens, and civil organizations. Its objective is to increase the velocity at which the changes are done in order to achieve the goals stated by the European Green Deal [4].

In order to assess the potential outcomes of the stated goals in the EU Green Deal, extensive research was conducted to examine the current scenarios. The findings revealed that different organizations provided forecasts based on either an energy and economic perspective [5] (Capros, A de Vita, A.Florou) or specific sectors i.e., heating and cooling of the EU are investigated. [6] (W.Nijs, P.R.Castello, I.H.Gonzalez, G.Stiff). The primary goal of the mentioned scenarios is to determine if the current development of different energy technologies i.e., power to heat, domestic appliances and equipment, industry, transport or RES like PV-systems, wind power generation, etc. will meet the EU policy targets. In order to do so the first analyzed scenario [5] (Capros, A de Vita, A. Florou) presents the influence of technological development as well as the evolution of the population, economy, and fuel prices of the EU-27 on the transport sector, GHG emission, and the energy system. To achieve the stated goals, this study utilized different models i.e., PRIMES Energy, Primes Industry, etc. to better anticipate the interactions between different energy system sectors as well as the impacts of the chosen policies. The results of the mentioned scenario enable a projection of the future energy system based on the current policies. The second scenario [6] (W. Nijs, P.R.Castello, I.H. Gonzalez, G.Stiff) primarily focuses on the cooling and heating sectors of the EU-28 and similarly to the first scenario, applies a specific model i.e., JRC-EU-Times to determine the best combination of energy technologies to meet the EU goals.

Both scenarios present their forecasts or projections concerning the efficiency of the energy system based on the efficiency of applied energy. Energy usage alone does not define how efficiently a system operates. Therefore, this thesis applies a new approach to determine the best technology mix of the future as well as the efficiency of the overall system. In this work, an exergy-based approach is computed. Such an approach was never applied on a European scale before, only the Austrian energy system was analyzed based on this method [7]. (C.Sejkora) An exergy-based approach has a multitude of benefits for the development of the future energy system. On the one hand, exergy considers the quality of the energy used and therefore offers a deeper insight and understanding of the energy system. On other hand it enables the comparison of different types of energy and identifies the sectors which demand action in order to increase their efficiency [8, 9]. An exergy analysis does not consider the current expectation or political influences but takes into consideration only the technical aspects of different technologies. Moreover, to better present the future energy system, the entire conversion chain is considered. Figure 1 presents the structure of the current energy system. Analyzing the entire energy conversion process includes evaluating the energy input, conversion process, and output. The consumption of electricity by end-users involves several conversion processes, which are dependent on the primary energy carriers used. In the first step the primary energy carriers, such as coal, must first be extracted before they can be converted into secondary energy. Conversely, the RES can directly be converted to secondary energy. The output of the first category is used as an input for the second category which represents the energy supply system. In the second step the primary energy is converted into secondary energy, after which i.e., the generated electricity is transported to end-users via high-voltage transmission lines. The secondary energy is also referred to as final energy. The final exergy is provided at the right place, which means there where the end user needs it, also at the right time, meaning that whenever the end consumer wants to access it, must be possible and in the right form for example electricity etc. The last characteristic of the second category is the presence of conversion units and storage. The third step is represented via final exergy applications. Their purpose is basically to convert the final energy in useful exergy. The useful exergy is then consumed by different passive elements i.e., light bulbs in households. Lastly, the fourth step stands for the current useful exergy demand, meaning that the needs of any person in the analyzed system must be covered at any time with no boundaries.

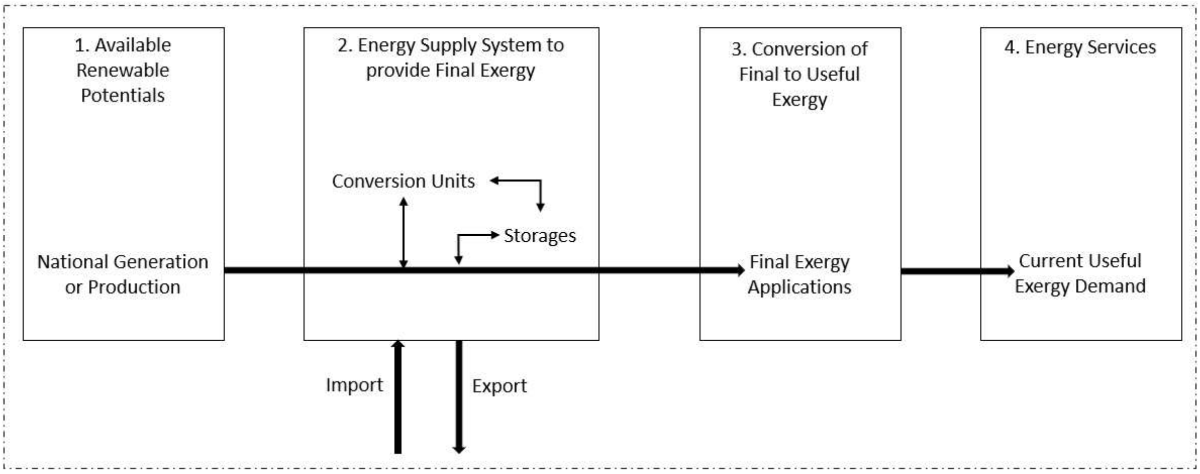

Figure 1: Structure of the current energy system

To determine if the desired goals stated by the EU will be achieved the optimization environment Open Energy System Modelling Framework (oemof) is utilized in combination with the green field approach which means that the system has no restrictions in the way it decides how the optimal technology mix of the future energy system will look like. Oemof tool has a predefined function, namely, to reduce the primary exergy of the entire energy system. Subsequently, the efficiency of the energy system will be determined. Based on the fact that the European energy system was never analyzed using an exergy-based approach, the following research questions are formulated which subsequently will be answered.

Which technologies find their application in 2050?

What does the energy generation in 2050 look like?

Is the EU supply enough to cover the entire demand within its boundaries?

How efficient is the future energy system?

The thesis is structured into specific chapters. In Chapter 2, the methodology used to gather the data is described. Chapter 3 provides insights into each sector analyzed and explains the assumptions made to calculate the exergy values for 2050. Chapter 4 presents the results of two investigated scenarios and draws a comparison between the current state, referred to as EU-27* in 2019, and the projected EU-27* condition in 2050. These findings will be further discussed to gain a comprehensive understanding of the future energy system and its level of efficiency. In Chapter 5, the conclusions and potential areas for future investigation based on the current results are presented.

2 METHODOLOGY

As mentioned in Chapter 1 the EU set certain goals for 2050 that is desired to achieve. Norway and Switzerland are not members of the EU, but still have an impact on the European energy system since they are connected to the international grids, therefore their influence on the overall energy system is also considered. Therefore, these countries and their development are also considered. The EU members with Norway and Switzerland are defined in the course of this work as EU-27*.

To achieve the desired targets stated by the EU, it is imperative to reduce Primary energy consumption (PEC). Multiple approaches can be utilized to manage such changes. On one hand, is the modifying of overall behavior i.e., by making shifts in modal split, improving systems such as thermal insulation, and reducing the mass of vehicles, and on the other hand, enhancing the overall efficiency of the applied technologies. These measures result in a reduction in PEC. Another viable approach is to improve the total energy efficiency of the entire energy conversion chain. This involves identifying and implementing necessary measures to reduce PEC. Furthermore, reducing PEC can have significant positive environmental and economic implications. By minimizing energy consumption, the production of GHG and other pollutants can be mitigated, leading to a cleaner and healthier environment [7].

To gather a better understanding of the methodology applied to model the future energy system Figure 2 is used. Firstly, the Final energy consumption (FEC) in 2019 was investigated. This data was provided by the Forschungsgesellschaft für Energiewirtschaft (FfE) organization within the framework of the EXTREMOS project [10]. By utilizing a holistic European energy system model, this organization has the capacity to create maps that depict the coupling of European electricity markets and scenarios, with the aim of providing modalities of the EU by 2050. To ensure a high level of detail, FfE amalgamated information from diverse sources and developed a methodological approach to integrate the data [10]. The data was divided into different sectors i.e., industry, services, transportation, and households. The transport sector in the FfE database does not distinguish between the type of used vehicle or driven range of kilometers (km) therefore, the data pertaining to the transportation sector, particularly the evidence utilized to make the assumptions outlined in subsequent paragraphs, were acquired from EUROSTAT. Chapter 3 presents a detailed mathematical computation in order to determine the Useful exergy demand (UED) for 2050. Furthermore, data for rail transport, both with and without power lines, domestic aviation, and navigation were obtained from ENTSO-E for EU-27. As previously mentioned, data for Norway and Switzerland were sourced from various organizations responsible for the generation and management of the gathered data. The FfE database provides information in regard to different energy carriers i.e., fuel oil, biomass, coal, natural gas, electricity, etc. Each energy carrier has different applications. The main applications provided by FfE are classified as mechanical energy, process heat at 100°C, 100-500°C and >500°C, process cold, lighting which consists of Light-emitting diodes (LEDs), fluorescent lamps and halogens and Information and Communication Technologies (ICTs). Lastly for each type of energy carrier and final application, a specific amount of energy in GWh is allocated.

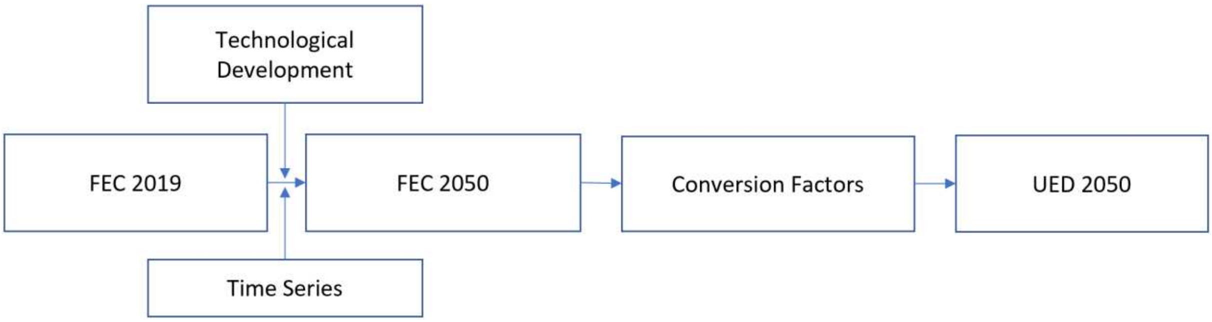

Figure 2: Methodology applied to determine the exergy demand in 2050 in EU-27*

Due to the fact that this thesis presents the exergy system of the EU in 2050, the trends in the technology development, population growth, and economic development are considered, and the findings are extrapolated until 2050. Based on (The Economist Intelligence Unit Limited 2015) the real Gross domestic product (GDP) is estimated to have an average growth of 1.40 % per annum [11]. Figure 3 is an illustration of the real GDP development of world regions. On the other hand, EUROSTAT provides demographical development [7]. Eurostat projected that the population of the EU will increase till 2026 and afterward will slightly drop achieving a population number of 441 million in 2050. This represents a -0.04 % change in comparison to the status quo value. The cumulative percentage change represents 1.36 % yearly. The technological development was chosen in accordance with NEFI [12]. It indicates that the stationary engines will develop a yearly rate of -0.25 %, the lighting and ICTs at a yearly rate of -0.16 %, and the thermal systems at a yearly rate of -0.49 %.

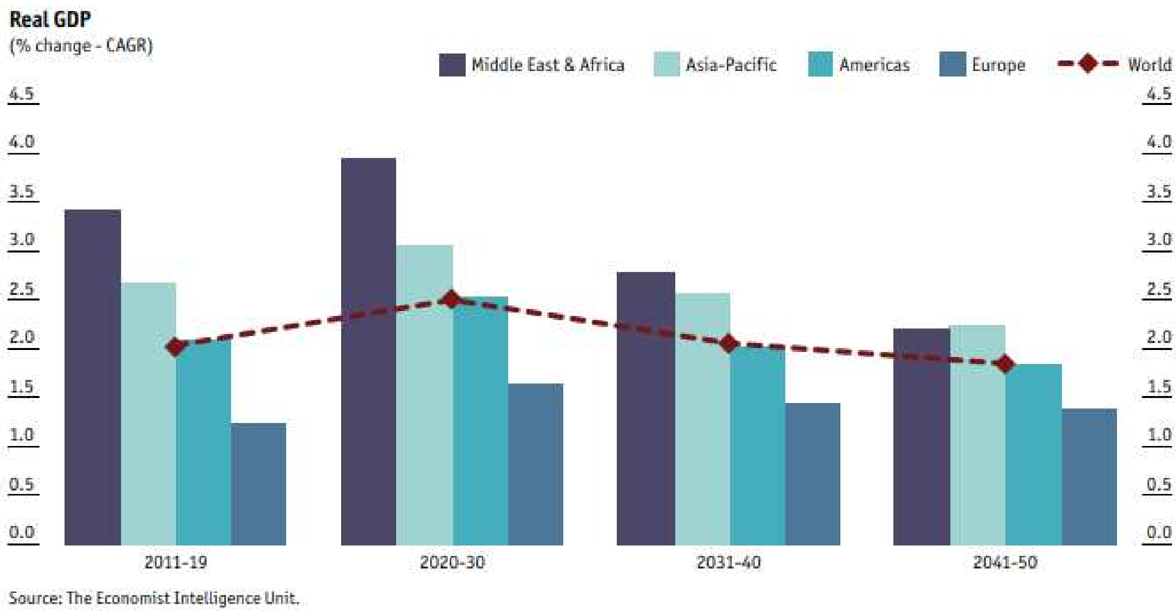

Figure 3: Development of the European real GDP [11]

The following step consists in acquisition of time series data for four distinct categories - namely solar power [13], wind power [13], hydropower [14], and heat profiles [15] - were determined. The ENTSO-E transparency database [13] was utilized to establish the time series for solar power and wind power generation, with a selection of data at intervals of 60 minutes.

I would like to point out that it is uncertain how the expansion will take place in Europe because each member of EU-27* has a different RES potential. Therefore, a single-node approach was applied, meaning that the overall production as well as consumption occure in the same place with no spatial distributions. Analyzing the south part of EU-27*, it is characterized by high solar potentials but low heat demand for buildings. The north and the west of EU-27* have a high wind potential, mainly represented through the offshore wind generating turbines. In the northern and central regions is the potential for hydropower systems due to geographical advantages more developed also accompanied by higher demand for space heating. [16]. In order to balance the entire system different weighting factors were utilized. The overall hourly production of one type i.e., hydropower generation of each member state was multiplied by the corresponding factor. This way the potential for errors is minimized. An in-depth classification of the utilized weighting factors is presented in Chapter 7. Following the weighting of production for each country, the total hourly energy production of solar power and wind power in 2019 was determined. The hydropower generation was determined using the same approach, except for the data source, which was obtained from Energy-Charts [17] for each country.

Beyond the time series of the hydropower plant, wind power plants, and photovoltaic systems, the heat profiles are researched. To be able to determine the time series of the heat profiles the SigLinDe function was employed. It combines the Sigmoid Function and the linear function. The SigLinDe profiles correct for systematic errors in the sigmoidal profile functions at the lower boundaries of the temperature interval, particularly at low-temperatures [18].

Due to the fact that no EU-Database provided such information, the hourly temperature data was gathered by (Pfenninger, Staffell) [15]. This source provides the time series for temperature profiles for each country separately. Subsequently, this data was integrated into a unified database. Next, the hourly temperature values were divided into 15-minute intervals with the assumption that the temperature remained unchanged during the hour analyzed. The hourly data was divided into 15 minutes values in order to enable the calculation of the heat profiles for all countries. Applying the same logic, that temperature has different applications in different categories such as households, industries, commercial and public services as well as agriculture and forestry sectors and it varies in the entire EU-27*. Therefore, to determine the heat profiles first of all the values were weighted based on Table 13 in. The weighting factors for the water power generation are provided by "Global Energy Resources database" [19]. On the other side, the weighting factors for photovoltaic systems as well as wind power generation are provided by "FfE country profiles" [20]. The households and industry sectors have the highest FEC, which stands for 2886 $\frac{\mathrm{TWh}}{\mathrm{a}}$ and 2784 $\frac{\mathrm{TWh}}{\mathrm{a}}$ respectively. Due to the fact that the household sector (one-family) has a higher FEC than the industry sector, they are used the basis for the determination of the heat profiles. The time series for certain sectors i.e., transport demand for heavy duty truck, transport demand aviation, transport demand pipelines, as well as the timeseries of the woody biomass generation, sustainable natural gas production, ethanol fuel and biodiesel production, waste accumulation and geothermal generation are constant over the entire analyzed year.

The next step consists in ascertaining the forthcoming values of the input parameters for the simulation was carried out utilizing Equation (1). In this context, FV denotes the future value, PV denotes the present value, n represents the number of years between FV and PV, and i represents the rate of change over the analyzed time frame.

$$FV = PV * (1 + i)^n \tag{1}$$

In order to determine the UED, the conversion factors for each step described in Chapter 1 must be considered in order to determine the useful exergy of each utilized technology. First, it is important to understand what exergy is and how it is determined. Exergy is a component of the total energy that can be effectively converted into useful work. It represents the maximum work that can be obtained from a material flow through a reversible process, following the principles defined by Carnot. Conversely, the energy that is not utilized or converted into work is referred to as anergy. Both exergy and anergy are significantly influenced by the ambient temperature (T_{amb}). Throughout this study, an ambient temperature of 10°C is assumed as a constant reference.

Due to the fact that the energy system is complex and different parameters are interlinked with each other, the oemof library was developed with the goal to provide tools for recurring tasks in energy system modeling. To be able to model the system the user combines different self-written applications with the oemof library. The oemof-network library is used to define energy systems as a network with components and buses. The components can be connected to one or more buses. Figure 4 illustrates the way in which the oemof-network is structured [21, 22].

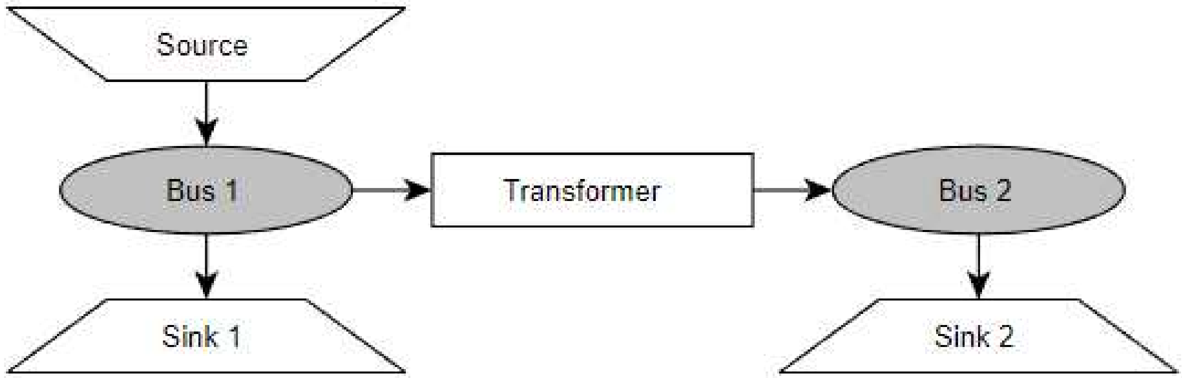

Figure 4: Structure of the oemof-network library [21]

To analyze Figure 4, one must note that all parameters in the system can flow into or out of a BUS, which represents a network without any losses. The FLOW class, represented by arrows, is used to connect the BUS with other classes such as SINK, SOURCE, and TRANSFORMERS. The SINK class is used to define the energy demand in the model and to identify any excess. On the other hand, the SOURCE class is used to represent the origin of the demanded energy, such as a photovoltaic or wind power system, or the import of other energy sources like gas. Depending on the source type, the values can be defined based on the ambient conditions or by specifying the maximum or minimum load and full load time in case of gas import. The TRANSFORMER class represents a node that has multiple input and output flows, such as power plants, transport lines, electrolysis processes, or heat pumps [23]. To enable the specification of the UEC in regard different technologies mentioned above the class MyBus was developed.

3 DATA ANALYSIS

This chapter presents the computing path for the main applications described in Chapter 2. Due to the fact that each application has its own technological development, certain calculations differ from each other, and all the differences are described in the corresponding chapters. The development of the RES in Switzerland was investigated using "Swiss Energy System 2050" [24]. Subsequently, the results of both scenarios are combined based on the weighting factors presented in Table 13 [19, 20]. The purpose is to determine the values for all applications in 2050. Subsequently, the simulation will proceed.

3.1 Primary energy supply

The following chapter deals with the analysis of the Primary energy supply (PES) for the EU based on two scenarios provided by two committees. The scenarios differ from each other in the amount of energy produced. The PRIMES Incumbent scenario [25] represents the technical potentials of the RES whereas the EU-Reference scenario [5] stands for a constant development of the RES. The goal is to analyze the supply side of the renewable energy sources and determine their amounts in 2050.

The first scenario analyzed was the EU-Reference scenario 2020 [5]. This scenario provided by the EU represents a projection of the development of the future energy system, the GHG, emissions and the transport system. In the EU-Reference scenario, the energy system of all the EU members is modeled and projections until 2050 as well as final energy demand and supply systems are made. Analyzing the bandwidth of the RES is to be stated that their supply doubled from 2018 (18 % of the overall supply) towards 2050 (36 % of the overall supply). It is also important to mention that based on this model the oil share did decline from 2020 from 32 % to 27 % in 2050 and still has an important share in the joint supply. One reason for this phenomenon is that there will be a limitation in the substitution of conventional energy carriers in the transport sector. Figure 5 (left side) illustrates the PES based on photovoltaic systems which accounts for 677 $\frac{\mathrm{TWh}}{\mathrm{a}}$, from wind power 1355 $\frac{\mathrm{TWh}}{\mathrm{a}}$ from hydropower plants is 372 $\frac{\mathrm{TWh}}{\mathrm{a}}$ and lastly from biomass constitutes 1849 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Due to the fact that the division between woody biomass generation and sustainable natural gas production was not performed the following assumption base on Bioeconomy [25, 26] is made, namely that the division between woody biomass and sustainable natural gas is 60 % and 40 %.

The second scenario (R.Rodrigues, R. Pietzcker, P. Fragkos, J.Price, W.McDowall, P.Siskos, T.Fotiou, G.Luderer, P.Capros) used to determine the electricity generation based on different energy carriers is based on the [25]. Detailed insight regarding the work of the model can be found in [25]. The result of the model is divided into three sections: the new players, the incumbents, and efficiency. In this thesis, the incumbent scenario is considered because it represents a completely different development of the RES when compared to scenario 1. The narrative of the incumbent section focuses on the supply-side change, and the implementation of large-scale technologies such as Carbon capture and storage (CCS) and nuclear. Therefore, this selection enables the analysis of two different case studies.

Figure 5 (right side) presents the results of the PRIMES Incumbents model in 2050. The electricity generated via wind power consists of 4006 $\frac{\text{TWh}}{\text{a}}$, via photovoltaic system is 1107 $\frac{\text{TWh}}{\text{a}}$, through the hydropower system is 415 $\frac{\text{TWh}}{\text{a}}$, the biomass generation overall is 710 $\frac{\text{TWh}}{\text{a}}$. Like scenario 1, no data pertaining to the division of the corresponding primary exergy supply through biomass into woody biomass and natural gas production was made. Therefore, the same assumption is made, namely that from the overall production 60 % are due to woody biomass and 40 % are for the natural gas production based on Bioeconomy [25, 26].

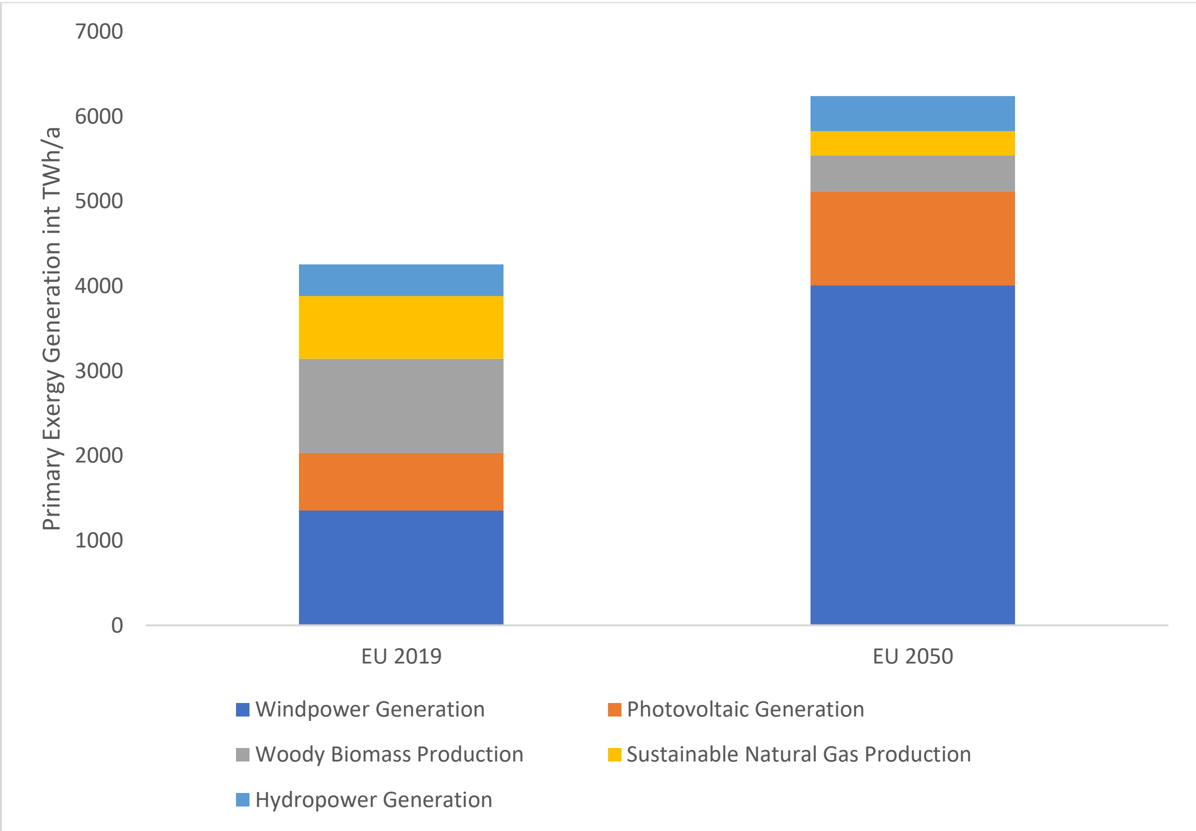

Figure 5: Primary exergy generation of scenario 1 (left) [5] and scenario 2 (right) [25]

3.2 Useful exergy demand in the transport sector

This chapter aims to analyze the UED of the transport sector in 2050. To achieve this objective, the transport sector has been categorized into two separate parts for analysis. The first part of this study concentrates on the exergy use of passenger cars while the second part assesses the exergy utilization of Light Duty Trucks (LDT) and Heavy-Duty Trucks (HDT). Differentiating between long and short-distance travel is crucial due to the distinct technological developments associated with the LDT and HDT, which are closely tied to the type of engine used on a daily basis. These technological disparities directly impact the type of energy consumed during travel. This differentiation allows the oemof system to choose the most efficient final exergy technology and therefore increase the efficiency of the entire system.

3.2.1 Passenger cars

At a European level no data is presented regarding the distribution of cars based on the km driven. Therefore, certain assumptions were made. The primary objective is to construct an accurate portrayal of the sector's progression throughout Europe. To achieve this, Germany is selected as the reference country for the following reasons. First and foremost, the economic development of a country was taken into account. In this regard, the length of the road network serves as a proxy for economic development, as improved road infrastructure facilitates swifter travel between destinations. With a total length of 13183 km, Germany boasts one of the most extensive motorway networks in Europe, outpacing other comparable countries such as France (11671 km), Italy (6966 km), and Spain (15585 km). Table 1 illustrates the length in km of four categories of roads: motorways, main or national roads, secondary or regional roads, and other roads in the European countries [27].

Table 1: Motorway length in the EU [27]

Country	Motorways	Main or national roads	Secondary or regional roads	Other roads
Belgium	1763	13229	1349	138869
Bulgaria	790	2900	4019	12170
Czechia	1276	5826	48666	74919
Denmark	1346	2603	70900	
Germany	**13183**	**37842**	**178751**	**-**
Estonia	161	3850	12595	42461
Ireland	995	4314	13120	80548
Greence	2098	9299	30864	75600
Spain	15585	14870	135171	501053
France	11671	9522	378693	704201
Croatia	1310	7049	9523	8831

Italy	6966	23335	135691	69098
Cyprus	257	5461	2394	4950
Latvia	-	1673	5448	62022
Lithuania	403	6679	14559	50870
Luxembourg	165	839	1891	19
Hungary	1723	30128		188551
Malta	-	520		2120
Netherlands	2790	2668	7813	127173
Austria	1743	10858	23653	91238
Poland	1676	17775	153675	251789
Portugal	3065	6457	4791	-
Romania	866	17007	35083	33435
Slovenia	623	5917	32087	
Slovak Republic	495	3594	13972	39671
Finland	926	12538	13469	50992
Sweden	2133	13556	140803	42805

Despite variations in motorway lengths, the average travel time from home to work in European countries is approximately 26 minutes. Figure 6 provides a visual representation of the mean travel duration from individuals' residences to their workplaces. The extent of motorways could potentially impact the distances people traverse, which will be considered in subsequent analyses.

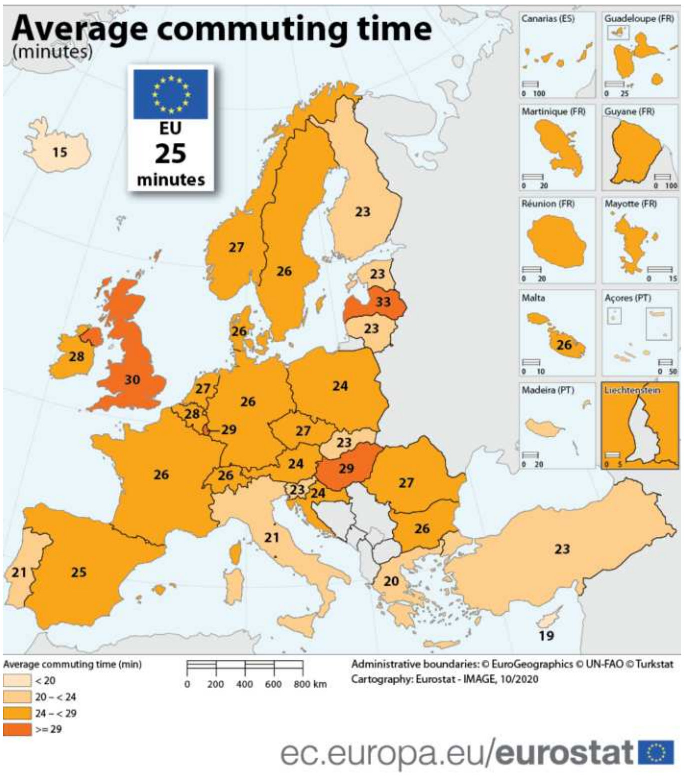

Figure 6: Average travel-time from residence to work in EU [28]

Additionally, the analysis encompassed an assessment of the average daily travel distance per person, contingent upon their primary mode of transportation. The findings reveal that the proportion of individuals using cars as their main mode of transportation is considerably greater than any other means of transport, and this trend remains consistent across all examined countries. In order to offer a more comprehensive perspective on transportation patterns in Europe, various country samples were scrutinized based on the categorization initially established by EUROSTAT. Table 2 presents the countries and their corresponding percentages. Passenger cars are the most prevalent vehicles for transportation purposes, utilized in diverse ways such as personal use, taxis, or carpooling. Buses and coaches constitute the second most common mode of transportation, while trains and urban rails are used less frequently [29].

Table 2: Travelled distance per person per day by travel mode in percent [29]

Travel mode	BE	DK	**DU**	EL	HR	IT	NL	AT	PL	PT	SI
By car as driver	54.4	53.8	**58**	44.6	59.6	63.7	49.6	50.6	48.2	57.3	65.2
By car as passenger	16.3	11.3	**15.4**	15.4	13.3	10.6	12.6	13.5	10.6	12.9	15.4
By taxi (as passenger)	0.1	0.3	**1.3**	1.3	0.4	0.2	0	1.1	0	0.4	0.2
By van/lorry/tractor/ camper	0	8.1	**0.8**	0.8	2.3	0.1	0	0	0	0	1.1
By motorcycle and moped	0.8	0.9	**7**	7	0.1	2.8	2	1	0.6	1.3	0.2
By bus and coach	4.3	4.1	**11.5**	11.5	9.9	7.2	3.7	4	25.9	10.8	6.8
Urban rail	2.8	4.4	**12.8**	12.8	5	2.5	0	13	2.9	4	0
By train (regular and high speed)	8.6	5.5	**0.1**	0.1	2.8	3.8	7.5	9	2.9	5.1	1.3
Aviation and waterways	0	0	**0**	0	0.2	0.1	0	0	0	0.5	0
Cycling	6.6	7.5	**0.5**	0.5	2.1	1.9	16	3.4	4.7	0.5	3.3
Walking	3.8	4.1	**5.8**	5.8	4.5	6.8	5.1	3.9	1.8	5.8	6.5

Figure 7 provides evidence substantiating the initial assumption that Germany can serve as a reference country for the distribution of passenger cars across European nations. The data illustrates that, on average, various European countries employ cars to a degree similar to that of Germany. Consequently, Germany functions as a midpoint, balancing countries with lower car usage, such as Hungary, with those with higher car usage, like Cyprus.

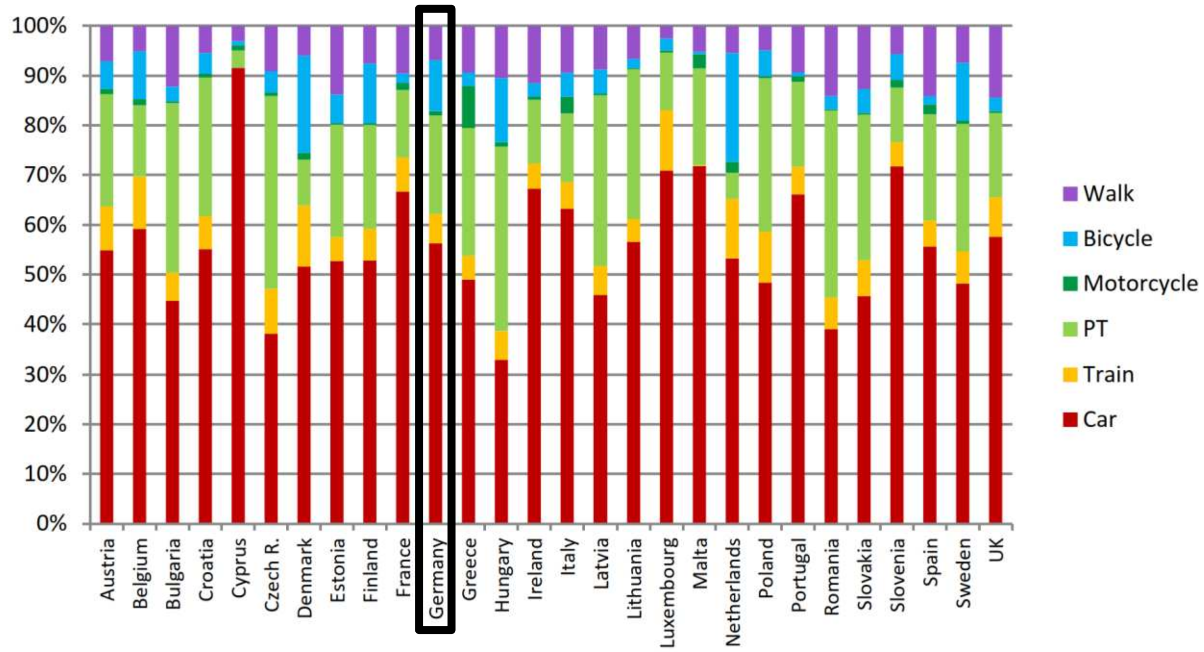

Figure 7: Percentage usage of passenger cars in EU [30]

It is also crucial to examine the purposes for which cars are utilized in society. Assuming that the distance traveled to work and professional or business travel distances are equivalent, the analysis of the presented sample reveals that Germany employs cars for these purposes in nearly 55 % of cases [29].

Figure 8 indicates the distribution of distance traveled per person per day by traveling purpose for urban mobility on all days. From the sample presented all countries drive to work as well as for business and professional purposes approx. 50 % which is as high as the percentage provided for Germany. The second most common reason for urban mobility is shopping and escorting. In Germany this type of traveling accounts for approx. 40 % as well as in Latvia. In other countries like Austria, it represents 35 %, in Slovenia it accounts for 42 %, Greece and Portugal share the same ratio, namely 35 % respectively. Therefore, considering the urban mobility of the EU member states it was assumed that on average the distance traveled corresponds to that of Germany.

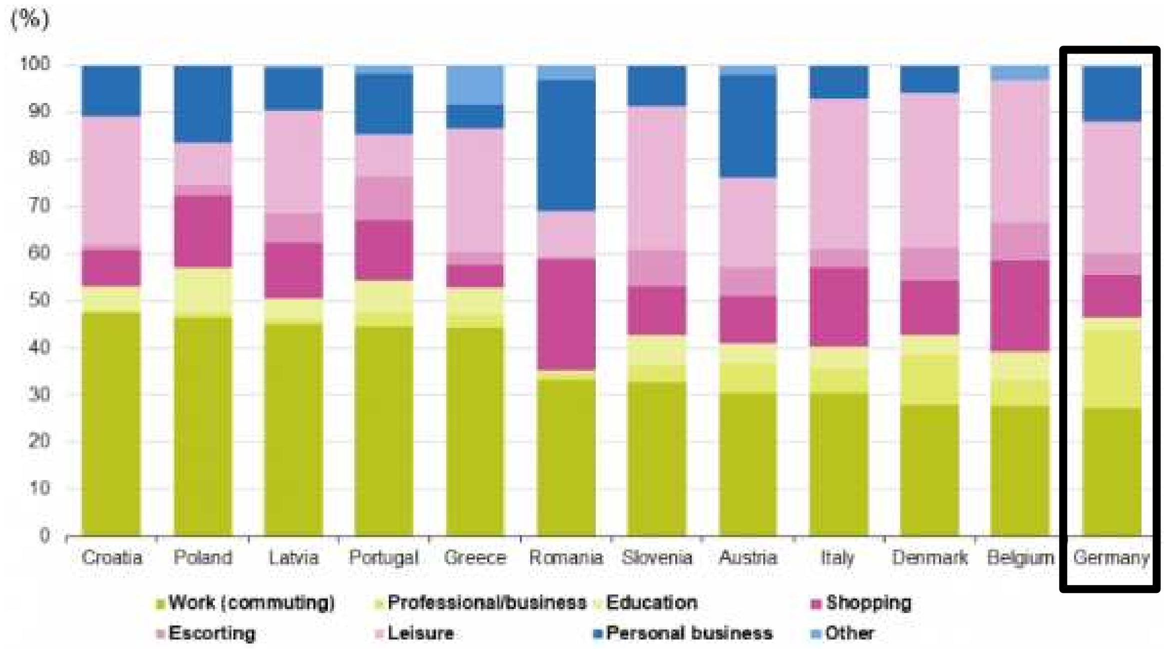

Figure 8: Percentage of distance traveled per person by travel purpose [29]

It is also imperative to take into account the integration of public transport throughout Europe, distinguishing between rural and urban areas. In rural regions, private vehicles predominantly serve as the primary mode of transportation, while public transport prevails in urban settings due to traffic congestion. Examining the broader picture of annual passenger kilometers traveled in various countries, private vehicles emerge as the most utilized mode of transportation, followed by buses and coaches, trams and metros, and railways. However, when analyzing each country individually, the majority of European nations display similar average values for annual passenger kilometers traveled [27, 29]. To verify this assumption, it is necessary to examine the overall percentage share across all sectors. In this regard, Figure 9 portrays the percentage distribution of passenger cars in the EU, corroborating our assumption.

	PASSENGER CARS
EU-27	81.3
EU-28	82.0
BE	80.4
BG	81.3
CZ	67.0
DK	82.2
DE	83.4
EE	79.5
IE	81.5
EL	81.9
ES	83.0
FR	82.0
HR	82.7
IT	81.4
CY	81.5
LV	84.0
LT	90.6
LU	82.4
HU	69.6
MT	82.9
NL	85.1
AT	71.7
PL	79.6
PT	87.3
RO	74.6
SI	86.6
SK	73.3
FI	83.2
SE	80.7
UK	86.1
ME	96.6
MK	87.4
AL	89.6
RS	73.8
TR	71.0
IS	88.8
NO	87.8
CH	76.9

Figure 9: Percentage share of passenger cars in EU [27]

It is worth noting that some countries, such as the Czech Republic with a 67 % car usage rate, and Hungary with a 69.6 % car usage rate, deviate from the average usage observed in the majority of European countries. Conversely, Lithuania is characterized by an exceptionally high car usage rate of 90.6 %. However, as previously mentioned, the limitations of the analyses tend to balance each other out.

The choice of Germany as the reference country is due to its economic development, road network, and average car usage. These findings indicate that Germany offers an appropriate reference point for the analysis. Therefore the differentiation between short and long distances traveled in the entire EU-27* is based on the same km-division as in Germany [31]. For the purpose of this thesis as short-distance travels are one <400 km and as long-distance travels are one >400 km. Based on Figure 10 the percentage of cars driving less than 400 km is 95 % and more than 400 km is 5 %. This information is further illustrated in Figure 10.

	50-100 km	100-200 km	200-300 km	300-400 km	400-500 km	500-600 km	600-700 km	700-800 km	800-1100
reference approach, passenger transport	43.83%	31.31%	13.45%	6.74%	3.26%	1.13%	0.26%	0.03%	0%

Figure 10: Share of driven km by traveling mode in Germany [31]

To determine the final exergy consumption of passenger cars in 2019, a specific methodology was employed. The initial step involved acquiring the total final energy consumption of the road sector from FfE, which amounted to 3454 $\frac{\mathrm{TWh}}{\mathrm{a}}$. This value encompasses the final energy consumption of freight vehicles and does not differentiate between primary energy carriers such as gas, oil, and electricity. A thorough analysis yielded the following results, noting that the electricity sector includes electricity generated from both renewable sources and other sources:

- Electricity - 243 $\frac{\mathrm{TWh}}{\mathrm{a}}$
- Gas - 45 $\frac{\mathrm{TWh}}{\mathrm{a}}$
- Oil - 3166 $\frac{\mathrm{TWh}}{\mathrm{a}}$

An additional assumption is made, namely that the freight sector is divided into two categories. The first category consists of freight transport using fossil fuels as energy carriers, making up approximately 95 % of all vehicles, while the remaining 5 % are electric vehicles [32].

The subsequent step involved subtracting the energy consumption of freight transport, as shown in Figure 11, from the overall energy consumption provided by FfE. It is crucial to differentiate between various energy carriers. The FEC of the freight sector using electricity as an energy carrier amounts to 76$\frac{\mathrm{TWh}}{\mathrm{a}}$, while oil and gas constitute 1451 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Thus, the FEC of electric passenger cars is 167 $\frac{\mathrm{TWh}}{\mathrm{a}}$,and that of passenger cars using oil or gas as an energy carrier is 1770 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

The second step entailed determining the number of kilometers driven by passenger cars in the EU in 2019, which was obtained from source [33] as 4325 billion passenger-km. The number of people in a vehicle is essential for determining final energy consumption. According to [29], the average number of people in a car during a trip ranges between 1.20 and 1.90. A value of 1.5 was selected for this analysis.

The third step in this study involved estimating the number of kilometers driven in EU-27* in 2050. Based on the economic and demographic development in the EU-27*, 6574 billion pkm are projected for 2050. It is assumed that the number of people sharing a car during a trip would remain constant at 1.5. Consequently, applying Equation (1) the FEC for passenger cars in 2050, with electricity as an energy carrier, is 380 $\frac{\mathrm{TWh}}{\mathrm{a}}$, and with gas and oil, it is 4036 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Considering a conversion factor (Table 8) of 0.90 from final energy to useful energy for electricity as an energy carrier and a conversion factor of 0.74 from useful energy to useful exergy, the total exergy demand amounts to 254 $\frac{\mathrm{TWh}}{\mathrm{a}}$. For gas and oil, the conversion factor from end energy to useful exergy is 0.3, resulting in an exergy demand of 1211 $\frac{\mathrm{TWh}}{\mathrm{a}}$ for this type of energy carrier. The combined exergy demand is 1464 $\frac{\mathrm{TWh}}{\mathrm{a}}$. The percentage distribution presented in Figure 10 enables categorization of trips taken by passenger cars into short and long-distance travel. Specifically, 95.32% of trips were identified as short distances, while the remaining 4.68 % were classified as long distances. These findings are presented in the accompanying Table 3.

Table 3: Useful Exergy demand of the passenger cars in EU-27* based on traveled distance.

UED for short distance <400 km	UED = 0.95*1464 $\frac{\mathrm{TWh}}{\mathrm{a}}$ = 1396 $\frac{\mathrm{TWh}}{\mathrm{a}}$
UED for long distance >400 km	UED= 0.05*1464 $\frac{\mathrm{TWh}}{\mathrm{a}}$ = 69 $\frac{\mathrm{TWh}}{\mathrm{a}}$

3.2.2 Light-Duty trucks and Heavy-Duty trucks

The second part of the analysis involves examining the development of LDT and HDT in EU- 27*. To project the energy consumption of freight road transportation in 2050, Figure 11 is utilized, where the y-axis represents the final energy consumption in Mtoe. According to the figure, it is estimated that the energy consumption for this sector will reach 131 Mtoe by 2050, equivalent to 1527 $\frac{\mathrm{TWh}}{\mathrm{a}}$ [34].

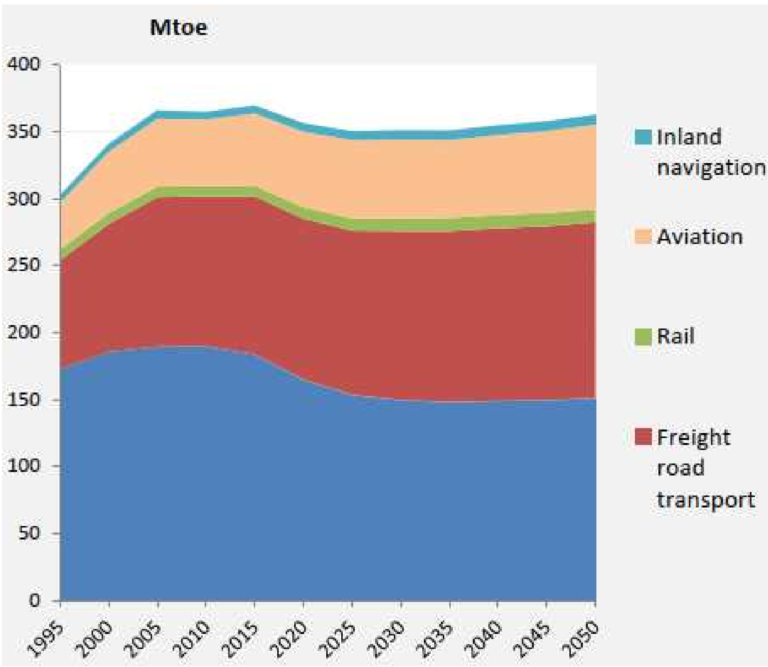

Figure 11: Final energy consumption of freight modes [34]

Afterwards it is important to identify the classification of the freight transport in EU-27* for 2050. To determine freight modal-split the following chart is used:

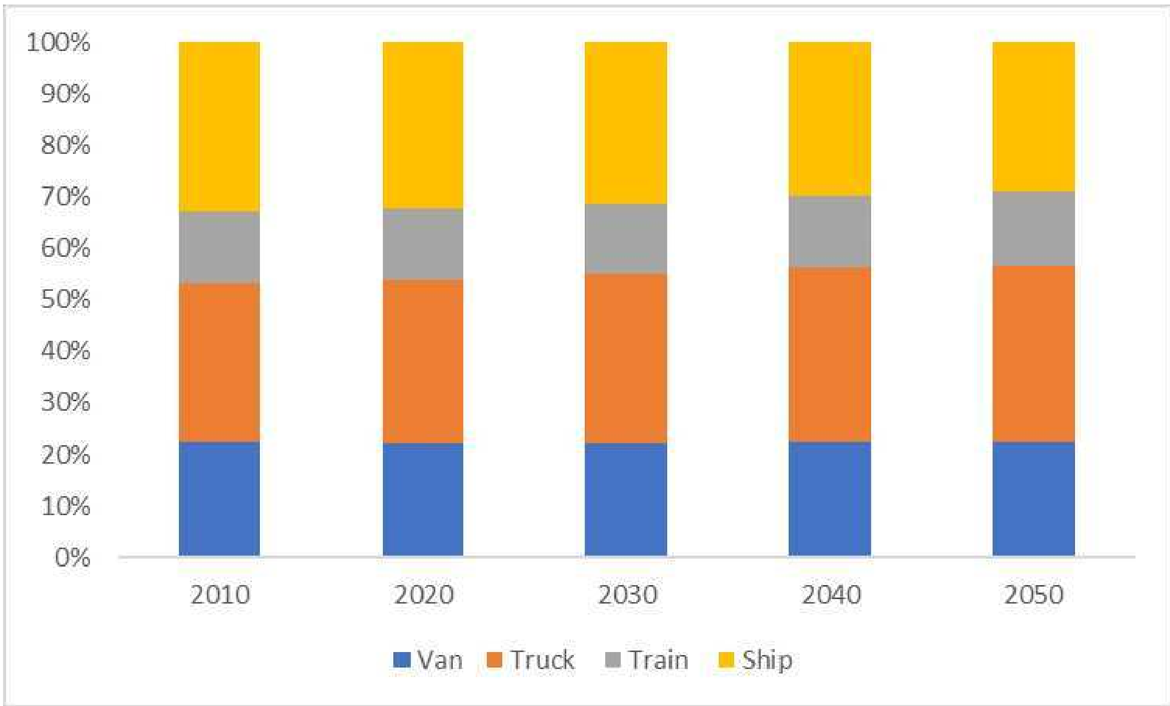

Figure 12: Freight modal-split [35]

Figure 12 is divided into four distinct categories, namely vans, trucks, trains, and ships. For this analysis, the primary focus is on vans and trucks because the rails as well as the navigation sector are analyzed in Chapter 3.5.3.2 and in Chapter 3.6 respectively. The chart displays the percentage distribution of these two categories from 2010 to 2050. Based on the study (N.Helfrich, A.Peters) described in [35] can be observed that the percentage deviation of vans remained relatively stable throughout the 40-year period. In contrast, trucks experienced an upward trend in terms of their percentage distribution, with an increase from 31 % in 2010 to 34.2 % in 2050.

Subsequently, the energy shares for each of the categories are calculated. To obtain the energy share, the percentages for vans and trucks in 2050, as presented in Figure 12, are multiplied by the final energy consumption of freight road transport, and an exergy conversion factor of 0.33 as indicated in Table 8 is considered. Table 4 provides the calculation of the UED.

Table 4: Useful exergy demand of LTD and HDT

$$\text{UED of Vans} = 22.4\ \% * 1527\ \frac{\text{TWh}}{\text{a}} * 0.33 = 113\ \frac{\text{TWh}}{\text{a}}$$

$$\text{UED of Trucks} = 34.2\ \% * 1527\ \frac{\text{TWh}}{\text{a}} * 0.33 = 172\ \frac{\text{TWh}}{\text{a}}$$

The categorization of freight road transportation into long and short distances is essential, and the initial assumption is based on the illustration presented in Figure 13. The diagram displays the percentage of European truck trips and their corresponding activity. It can be inferred from Figure 13 that the majority of truck trips in the EU-27* fall within the distance range of 100-700 km accounting for 75 % and distances exceeding 1000 km which correspond to 25 %.

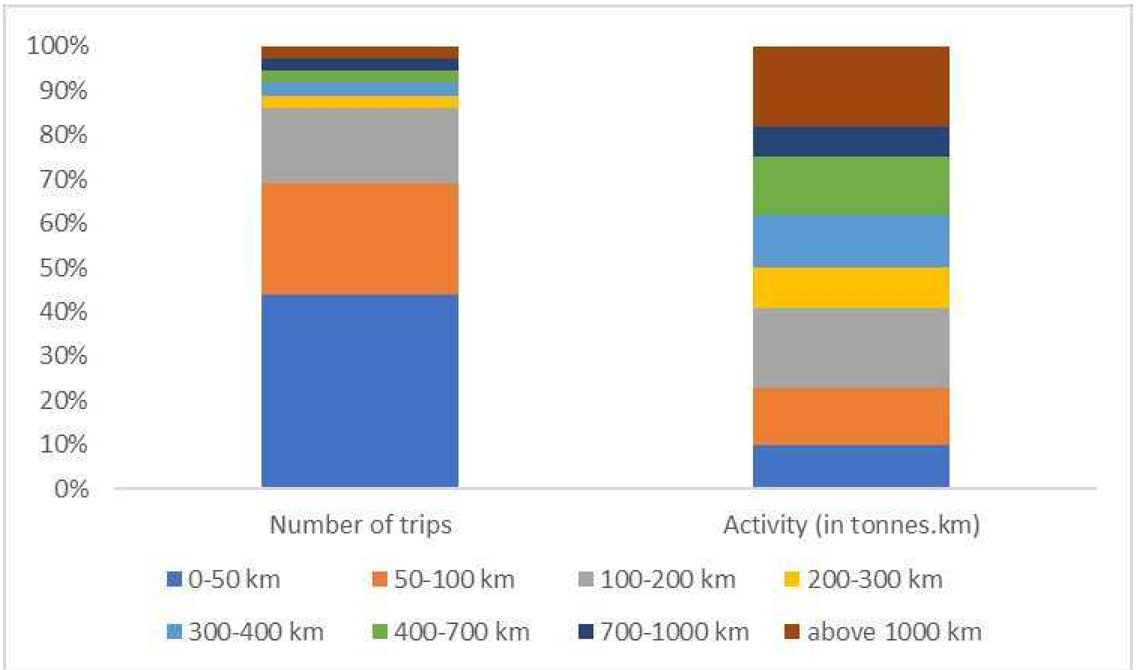

Figure 13: Share of EU truck trips and activity in percent [36]

This assumption leads to the following UED illustrated in Table 5:

Table 5: Useful exergy demand of HDT classified in short and long distance.

UED for HDT driving < 700 km	$\text{UED}_{\text{(HDT, Short)}} = 0.75 * 172 \frac{\text{TWh}}{\text{a}} = 129 \frac{\text{TWh}}{\text{a}}$
UED for HDT driving > 700 km	$\text{UED}_{\text{(HDT, Long)}} = 0.25 * 172 \frac{\text{TWh}}{\text{a}} = 43 \frac{\text{TWh}}{\text{a}}$

The subsequent stage involves determining the exergy consumption of vans that fall under the category of LDT in 2050. As reliable information pertaining to the traveled distance of LDT is scarce, Figure 14 is utilized to provide insight into the future development of vans. The diagram displays the development of the road vehicle fleet in the EU-27* from 2002 to 2050. In 2050, the LDT and HDT lines overlap, indicating that the deployment of these types of vehicles is predicted to develop similarly. Therefore, the percentage share for the LDT based on the number of trips and their activity is assumed to be the same as by the HDT. As mentioned above the differentiation between short and long distances for HDT is the 700 km mark. In the case of LDT, the differentiation between short and long distances is assumed to be 100 km. The reason for this assumption is described in further paragraphs.

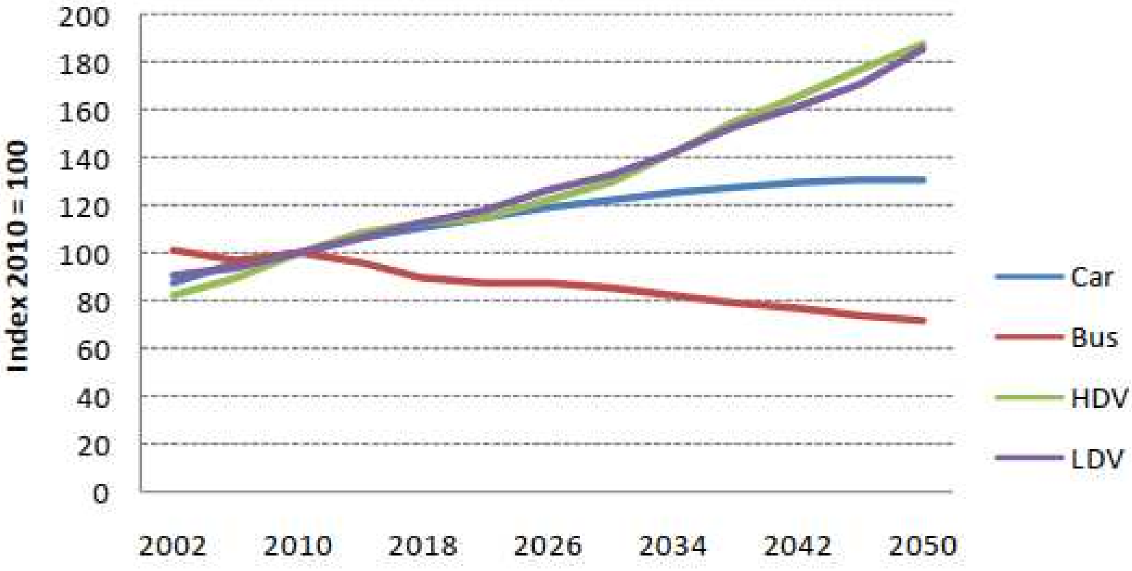

Figure 14: Development of road vehicle fleet in EU-27* [35]

In order to establish a reference value for the distance traveled by vans, the Netherlands is chosen as a sample country. Figure 15 presents the percentage distribution of annual distance traveled by registered vans in the Netherlands. The data indicates that approximately 60-65 % of the registered vans cover a distance of 25000 - 30000 km per year. This equates to a daily travel distance of 70-90 km or 100-120 km on working days, including weekends. Notably, vans covering shorter distances (dark blue) have an average annual distance traveled equivalent to that of high-distance vans (red), which represent 3.2 % of all registered vans.

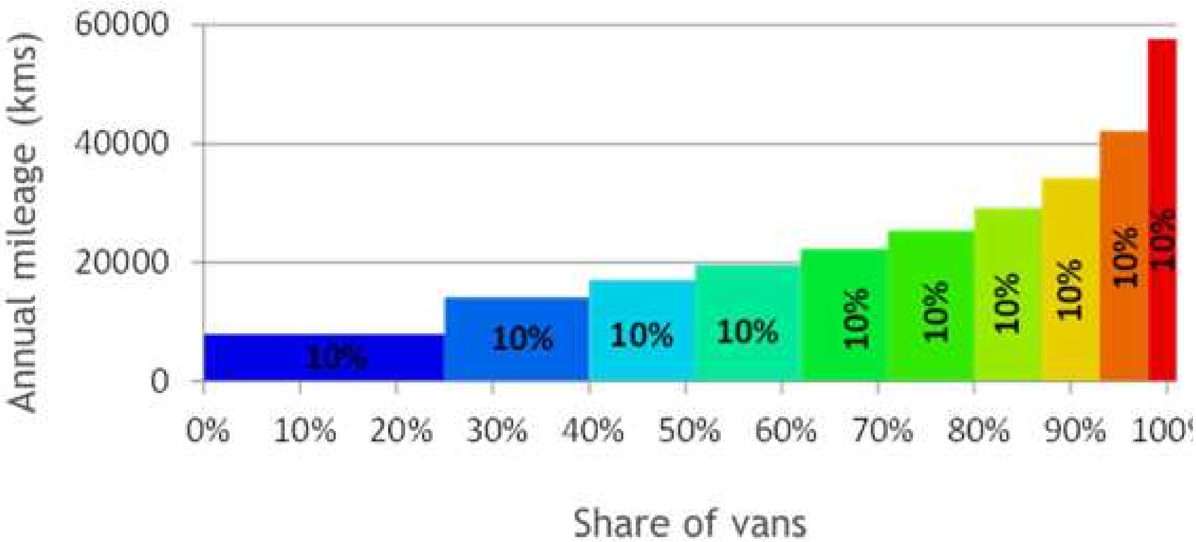

Figure 15: Annual mileage of vans in km [37]

Table 6 provides the computation path to determine the UED for the vans in accordance with the driven km.

Table 6: Useful Exergy demand of the vans classified in short or long distance.

UED for LDT driving < 100 km	$UED_{(LDT,\ Short)} = 0.32 * 113 \frac{TWh}{a} = 36 \frac{TWh}{a}$
UED for LDT driving > 100 km	$UED_{(LDT,\ Long)} = 0.68 * 113 \frac{TWh}{a} = 77 \frac{TWh}{a}$

Table 7 summarizes the exergy demand of the fright transport, namely LDT and HDT while distinguishing between short-distance and long-distance travels:

Table 7:Useful Exergy demand of the LDT and HDT

LDT_{Short}	$36 \frac{TWh}{a}$
LDT_{Long}	$77 \frac{TWh}{a}$
HDT_{Short}	$129 \frac{TWh}{a}$
HDT_{Long}	$43 \frac{TWh}{a}$

3.2.3 Pipelines

The primary objective of this chapter is to determine the exergy requirements for the transportation of energy carriers through pipelines in the EU by 2050.

The approach utilized to calculate the amount of energy required entails several steps. Initially, the proportion of energy allocated to the transportation of energy carriers through pipelines relative to the total gas demand must be determined. This necessitates an examination of the current state of affairs. Figure 16 illustrates the x-axis of the year and the y-axis the total gas demand in TJ. In 2019, EUROSTAT reported the total gas demand as 15423422 TJ, equivalent to 4284 $\frac{\mathrm{TWh}}{\mathrm{a}}$ [38]. Furthermore, EUROSTAT provided data on the FEC of transport via pipelines in the EU in 2019, which amounted to 2049 ktoe, equivalent to 24 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

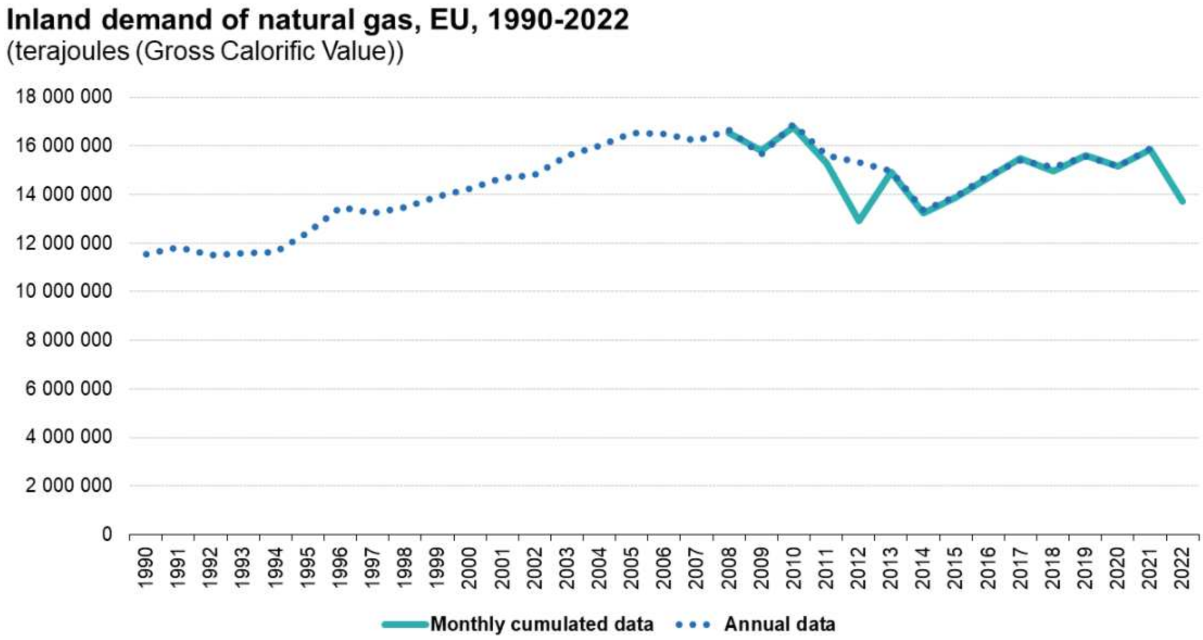

Figure 16: Inland gas demand in EU [38]

The subsequent step is to establish the percentage of energy consumption attributable to transport via pipelines relative to the total gas demand. The FEC for transport via pipelines accounted for 0.55 % of the total gas demand in 2019. The goal is to determine the exergy demand for this sector by 2050. To achieve this objective, the simulation assumed no exergy demand for transport in pipelines at the outset. Based on scenario 2 the results of the simulation indicate that approx. 9243 $\frac{\mathrm{TWh}}{\mathrm{a}}$ of gas will be required in order to cover the needs in 2050. The reason for choosing this scenario is due to the reduced dependency of gas imports in comparison to scenario 1. It is assumed that the ratio between the FEC and the total gas demand as stated in the status quo remains the same, namely 0.55 %. Therefore, the UED in 2050 was determined by multiplying the percentage ratio with the new gas demand. The result indicates that 51 $\frac{\mathrm{TWh}}{\mathrm{a}}$ are demanded the transport of energy via pipelines in 2050.

3.3 Demand non-energy use

This chapter presents a detailed description of the chemicals that have the most significant impact on the non-energy demand in Europe. The conventional and non-fossil methods of production for each chemical are presented, and the energy demands for both approaches are determined. Assumptions are made to estimate the energy demands of the entire sector in 2050, which are described in the corresponding chapters.

Petrochemicals form the basis of numerous products used in everyday life, such as thermal insulation, automotive parts, and packaging. This study analyzes only the major chemicals, specifically, ammonia, methanol, and urea are examined. To comprehensively map the entire sector, two critical questions must be answered:

1. What is the final energy consumption for the non-energy demand?
2. What is the impact of the circular economy on the chemical industry mainly on olefine and plastics?

3.3.1 Production route and exergy demand of the major chemicals

In the following chapters the production of ammonia, methanol and urea are described and the energy demand for the conventional and non-fossil way are determined.

3.3.1.1 Ammonia production and exergy demand

Ammonia (NH_3) is the second most widely used chemical globally. It has a vast array of applications, ranging from pharmaceuticals to refrigeration and mining, but its most common use is in the production of fertilizers [39].

To produce NH_3 different technologies can be applied. On one hand, is the conventional method where 1.33 tons of Carbon dioxide (CO_2) are emitted. In this case, the reaction between hydrogen and nitrogen in the presence of an iron catalyst is done. This reaction demands high temperatures and therefore high levels of heat integration occur as well as high pressure [40].

Another way of production is low-carbon ammonia production. In this method, no direct CO_2 emissions are produced, while the most energy-intensive step is the hydrogen production. The electricity demand for this step accounts for 10 $\frac{\mathrm{MWh}}{\mathrm{t\,NH_3}}$ and the compressor unit additionally demands 1.4 MWh. Figure 17 illustrates the low-carbon ammonia synthesis process.

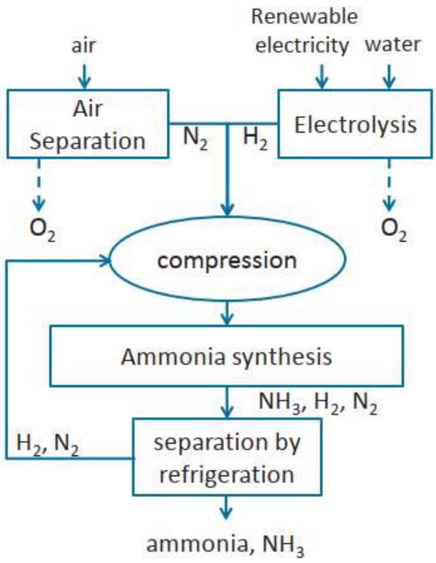

Figure 17:A production route of the non-fossil ammonia [40]

Thus, the overall energy demand is 12.5 $\frac{\text{MWh}}{\text{t NH}_3}$. According to "Low carbon energy and feedstock for the European chemical industry" [40], this translates to 178 kg of hydrogen needed to produce one ton of ammonia. The main obstacle to the implementation of this technology is its cost.

The production of ammonia is heavily dependent on the demographic and economic development of the EU (Chapter 3.3). Based on Equation (1), it is estimated that the production of ammonia in 2050 will reach 26.55 Mt, equivalent to an electricity demand of 331.86 $\frac{\text{TWh}}{\text{a}}$ [11, 40, 41].

3.3.2 Methanol production and exergy demand

Methanol is one of the most widely produced chemicals globally due to its versatile applications. [40] There are two distinct processes for methanol production.

The first way is conventional methanol production which occurs on one hand by using natural gas to create synthesis gas or by using CO or CO_2. For the ambient parameters and a detailed description of the conventional method visit [40].

The second approach for methanol production is known as low-carbon methanol production, which is considered low-carbon due to its utilization of water electrolysis to generate hydrogen. Figure 18 depicts the process of low-carbon methanol production. The low-carbon methanol production method is currently undergoing research to improve its economic efficiency. The production process involves water electrolysis, which is the most energy-intensive step. Based on the stoichiometric relationship, the production of one ton of methanol requires 189 kg of hydrogen, which is equivalent to 9.52 MWh. When considering the energy demand of other elements such as compressors, the overall electricity demand for producing one ton of methanol is estimated to be 11.02 MWh.

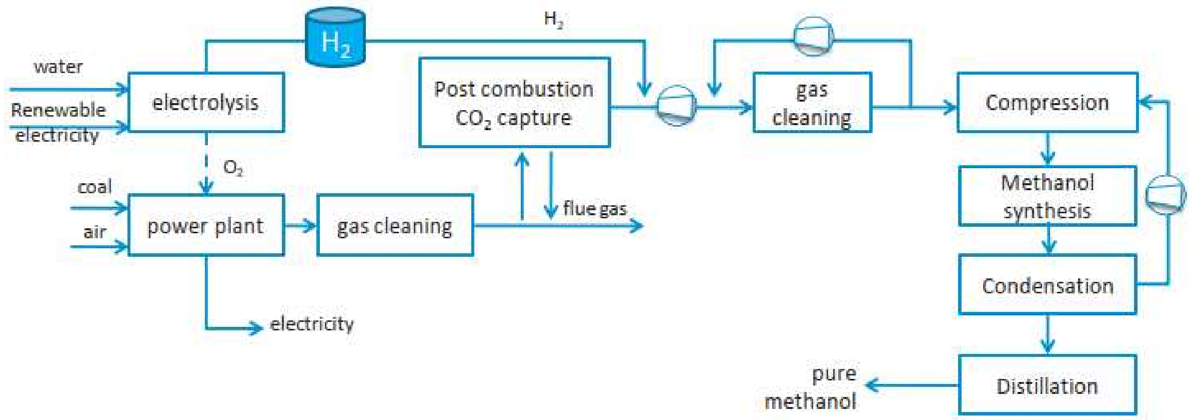

Figure 18: Low-Carbon methanol production [40]

Using the same approach for estimating the amount of methanol produced as for ammonia, it is projected that 3.40 Mt of methanol will be produced by 2050, equivalent to 37.34 $\frac{\mathrm{TWh}}{\mathrm{a}}$ [40].

3.3.3 Urea production and exergy demand

Urea has a wide range of applications, and it is primarily used as a fertilizer. The conventional process of urea production is primarily integrated into the ammonia production route, where the CO_2 required for urea production is generated through the reforming process. For a detailed description of this method visit [40].

The non-fossil production of urea is heavily dependent on the ammonia production route. If the ammonia production process is also non-fossil, then no CO_2 is generated in the ammonia reformer, and thus, CO_2 import is necessary. This implies that CO_2 can be reused and supplied into the system by capturing it from other processes, such as fossil-fueled power plants [40].

Determining the precise energy demand for urea production is challenging due to its close integration with the ammonia production process. For the production of one ton of urea, 0.57 tons of ammonia are required, which corresponds to an electricity demand of 7.1 $\frac{\mathrm{MWh}}{\mathrm{t\,Urea}}$. Considering the entire production process an overall electricity demand is equivalent to 8.05 $\frac{\mathrm{MWh}}{\mathrm{t\,Urea}}$ [40].

Given the high degree of integration between urea and ammonia production, and the lack of specific data regarding the proportion of urea production, it is assumed that urea production will increase proportionally to ammonia production. Thus, it is estimated that 9.36 Mt of urea will be produced by 2050, equivalent to 75.46 $\frac{\mathrm{TWh}}{\mathrm{a}}$ [36, 37].

3.3.3.1 Production of plastics via hydrogen-based methanol and exergy demand.

Ethylene and propylene production is primarily achieved through steam cracking, which uses naphtha as the main feedstock. In the recent years an recent increase in the utilization of Liquefied petroleum gas (LPG) in the European Union is observed [40].

An alternative approach for plastic production is low-carbon production via Methanol to Olefin (MTO). This method employs direct electrocatalytic processes to produce ethylene from CO_2 and water, eliminating the need for intermediary feedstocks like methane during olefin synthesis. The complete process comprises two stages: methanol production (described in Chapter 3.3.2) and its subsequent conversion to olefins. Determining the UED associated with the production of olefins is crucial. To calculate this UED, the chemical reaction was examined. Stoichiometric analysis reveals that producing one ton of ethylene or propylene requires 2.28 tons of methanol [40]. Consequently, the UED for this process comprises two factors: the energy needed for methanol production and the energy demand for the MTO process. The overall electricity demand for these two processes results in 26.6 $\frac{\mathrm{MWh}}{\mathrm{t\ plastic}}$ [40].

3.3.4 The impact of circular economy on olefine and plastics

Plastics are lightweight and cost-effective materials that offer extensive application possibilities, providing significant benefits to society in various sectors, including healthcare, construction, energy, transportation, and food. Consequently, the demand for plastics in the EU-27* currently stands at approximately 100 kg per person per year, with projections indicating that it may rise to almost 120 kg if the industry continues its current trend. [42] On the other side the olefins i.e., ethylene and propylene enable the production of plastics [43] However, to achieve circularity and net-zero carbon production in the plastic industry, a circular approach must be implemented. This way the 2050 targets can be achieved [42, 44, 45].

There are three main sectors that need to be addressed to achieve a circular use of plastics. Firstly, the feedstock sector, which currently involves the extraction and refinement of oil to produce naphtha and the use of natural gas to produce ethane which results in high CO_2 emissions. The solution is to use end-of-life plastics as feedstock to produce new plastics. Secondly, the production process itself, which produces plastic through steam cracking of naphtha and ethene, generates 2.3 tons of CO_2 per ton of product which results in an estimated 200 million tons of CO_2 emissions by 2050. To mitigate this issue, a more CO_2-neutral production process is needed, such as switching to an electrified polymerization process or producing plastics from chemical recycling. Chemical recycling is expected to play a crucial role in improving the plastic industry due to its efficient use of resources and ability to recycle contaminated or mixed polymers without downgrading their initial quality. Lastly, mechanical recycling technologies need improvements, as they downgrade high-value chemicals and have poor sorting quality. Improving mechanical recycling could avoid 2.7 Mt of CO_2 emissions from end-of-life incineration, while increased plastic reuse could reduce another 3 million tons of emissions annually. It is important to note that the circular use of plastics will require a significant shift in the mindset of the industry and consumers alike. This shift involves a move towards a more sustainable and responsible use of resources, which may initially entail higher costs for companies. However, the long-term benefits of a circular economy for plastics are vast, including a reduced environmental impact and increased resource efficiency. It is therefore crucial that policymakers and industry leaders work together to establish a clear path towards a circular use of plastics, with the ultimate goal of achieving a net-zero carbon future [42, 44, 46]. Figure 19 presents the anticipated plastic production volume from 2015 to 2050 in Mt. [42] In 2050 the production volume is estimated to be 72 Mt. Among the total volume, circular economy in major value chains accounts for 27 %, mechanically recycled plastics account for 18 %, bio-based production constitutes 27 %, and chemically recycled plastics produced through steam cracking amount to 28 %. The ReShaping Plastics model [47], estimates that 35.8 Mt of plastics will be recycled using the aforementioned techniques. Thus, the total amount of plastics to be produced in 2050 is expected to reach 36.2 Mt. Considering the UED for the production of methanol described in Chapter 3.3.3.1 an UED of 963 $\frac{\mathrm{TWh}}{\mathrm{a}}$ are forecasted by 2050 [11, 41, 42].

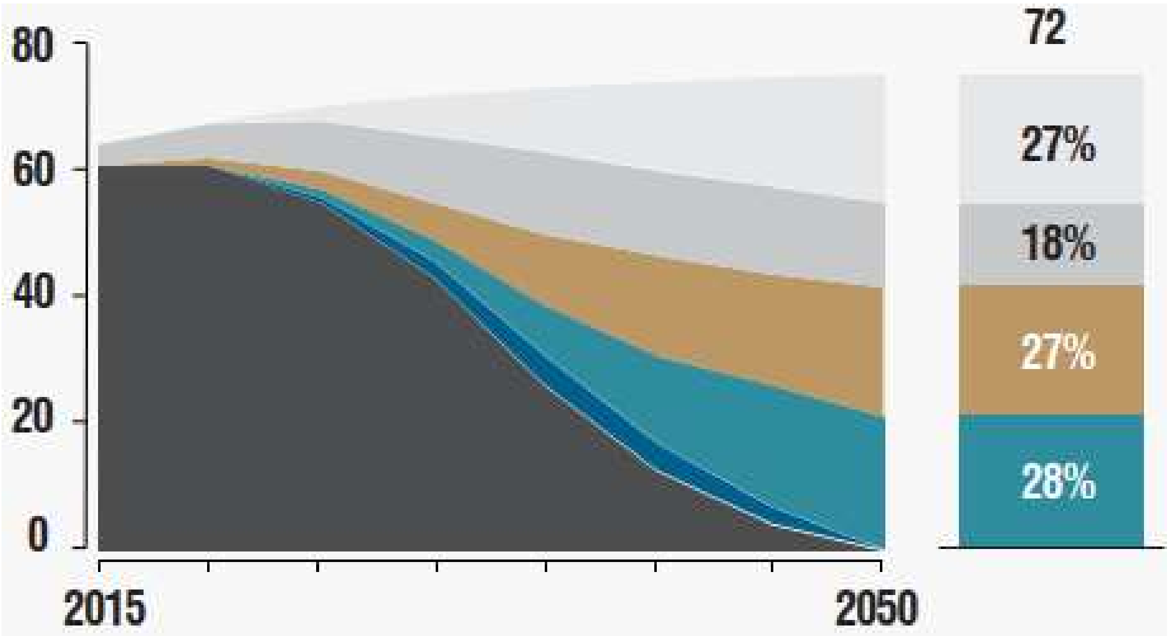

Figure 19: Plastic production via circular scenario in 2050 [42]

3.4 Exergy demand iron and steel making

The steel industry is of major importance for the European Union because this industry represents one of the most important sectors in the overall EU economy and at the same time offers a large possibility in the job market. Nevertheless, it is responsible for the major CO_2 emissions of the continent. [48] In the European Union steel production is mainly driven by four countries which are Germany (26 %), Italy (15 %), France (8 %), and Spain (8 %). Figure 20 represents the major steel-producing countries with the related process. The Basic oxygen furnace (BOF) and Electric arc furnace (EAF) process will be characterized and analyzed in future paragraphs. [49]

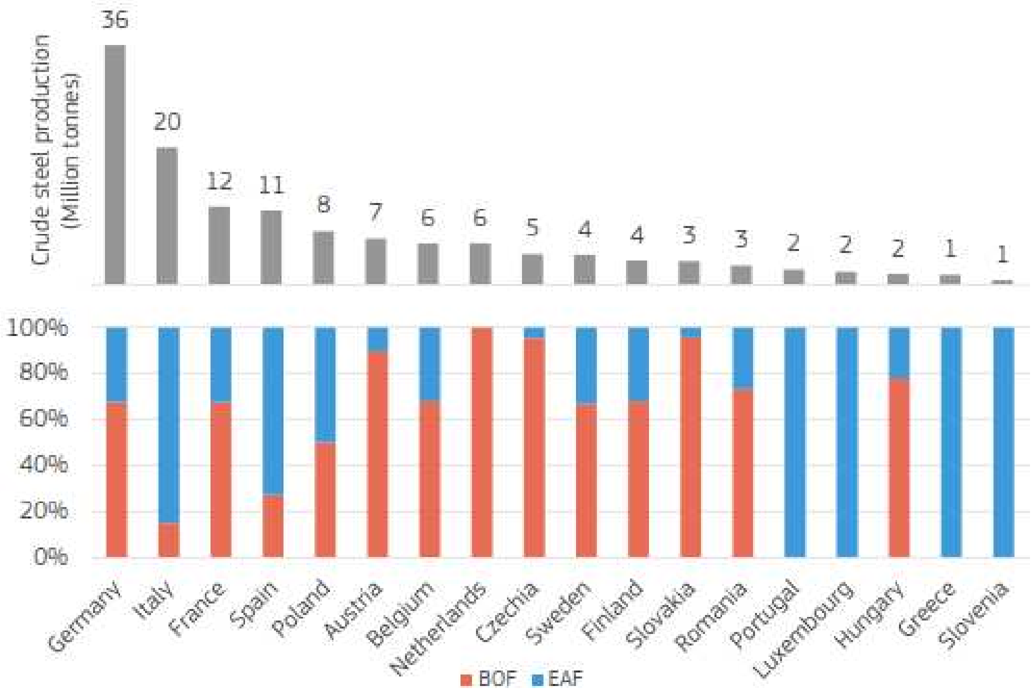

Figure 20: Steel production by member state [49]

Steel is used in almost every possible aspect of society, but the main industries are transport and machinery with a coverage of 16-17 % followed by construction and infrastructure with a coverage of approximately 50 % followed by metal products which cover the rest 15 %. Figure 21 illustrates the EU-27* steel production in Mt of steel per year starting with 2000 till 2050. [49–51] This figure indicates that the European steel stock reached the saturation phase in approx. 2008. Currently, the demand is 12 tons per person. It also indicated that the demand will decrease till 2050. The reason is a stagnation in population growth. Moreover, the EU steel demand will be entirely driven by the replacement of the current products which achieve their end-of-life phase. A slight increase in production would be possible due to increased exports. Overall due to the stabilization of consumption the EU-27* will manage to cover the demand by recycling the steel [50].

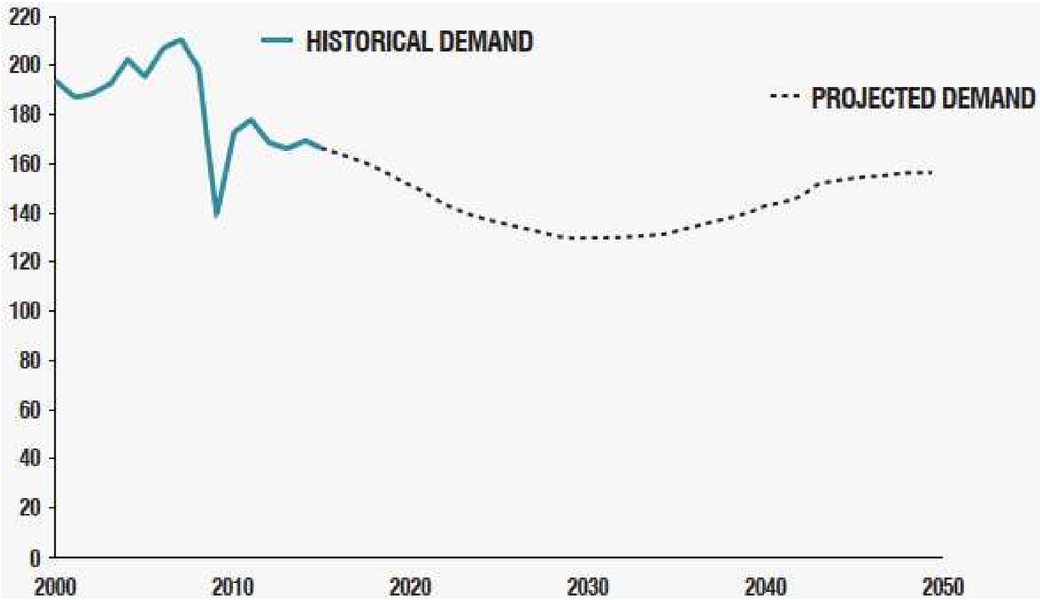

Figure 21: Steel demand by product group [50]

Given the fact that steel is widely used and is of strategic importance for the EU, adjustments regarding steel production should be made in order to meet the EU-27* goals. Through the steel industry in the EU 190 Mt of CO_2 was emitted which stands for 27.5 % of the total emissions.

In order to achieve the stated goals by the EU certain adjustments of the current process must occur. Therefore, the following paragraphs analyze the production and the cause for the increased amount of emission.

Steel can be produced in different ways. The first route is through the integrated steelmaking route, also known as primary steelmaking route. It is based on the Blast furnace (BF) or BOF. In this case, different raw materials are used like iron ore, coal, limestone, and recycled steel. The second way also known as the secondary steelmaking route is based on the EAF. In this way one-fifth of the CO_2 emissions are caused by primary steelmaking which results in high impacts on the environment [52]. Currently the primary steelmaking route is responsible for 56 % of the total steel produced. One of the reasons for the deployment of these route is the high quality of the produced steel [49, 50].

The question is how can the EU achieve the stated goals? The answer is to optimize the primary and secondary steel production or to introduce another technology.

Currently, the EU steel stock is approaching its peak at nearly 12 tons per person and at the same time the population growth now is constant and in the future is expected to decline. Therefore, the primary steel will be produced to improve the life standards of the third countries and to replace the actual products at the end of their lifetime which represents approximately 2-3 % of the total stock each year. This means that the market is saturated and a shift towards recycling will occur, meaning that the resulting scrap can be melted again and then used for production. Important aspects of the recycling of steel and the usage of scrap are the quality and quantity of the scrap. The quantity aspect is not a problem because based on different simulations the amount of scrap till 2050 will be enough to cover the most of future growth in steel demand with secondary steel [50]. The only concern is the quality because the steel undergoes different downgrading processes which make its quality worse. For example, the downgraded steel cannot be used in the transport sector, due to its inappropriate quality. In 2019 a total of 87.27 Mt was produced whereby to produce one ton of primary steel 6 MWh were needed. This means that the energy consumption for 2019 was 50.9 TWh [49, 50, 53].

The secondary steel production, as mentioned above, produces steel using the EAF, which means that high electricity demands are necessary. In the current situation the direct usage of electricity to produce one ton of steel is 0.5 MWh, if additional electricity for reshaping the product is necessary, also called downstream electricity then an additional 0.15 MWh will be used. This adds up to 0.65 MWh of electricity demand and 0.17 tons of CO_2 per ton of steel [54]. One way to optimize production is to use electricity generated by renewable sources. In this case, the process will be almost climate neutral. The only emissions originate from the process itself, i.e., burning of the graphite electrodes. Secondary steel production uses electricity as the main energy carrier but i.e., natural gas is also required in order to melt the scrap as well as coke or coal is demanded in order to increase the overall efficiency of the process [49]. Under current conditions to produce one ton of steel with the Electric Arc Furnace 2.5-3 GJ are required. In Europe in 2019 using the same method were produced 62.97 Mt of steel and countries like Norway and Switzerland produced together 2.07 Mt, which together result in 62.97 Mt of steel. In order to produce this amount of steel 43.73 TWh - 52.48 TWh are demanded [49, 53, 55].

The third way to make the steel production climate neutral is known as the Hydrogen Direct Reduction (HDR). The main difference to the primary steel production is that HDR uses another energy carrier, namely hydrogen as a reducing agent and not coke. This way the decarbonization rate can achieve 98 % in comparison with the conventional BOF route. To replace the primary steel production with the HDR route an amount of 50-60 kg of hydrogen is needed. Extrapolating these values to a European level indicates that in order to cover the total steel production of 92 Mt in 2019 with hydrogen an annual demand of approximately 5.5 Mt of hydrogen is required. In stark differentiation to the primary steel production procedure utilizing BF-BOF route, the iron ore does not undergo melting during the reduction phase. Alternatively, the HDR process is combined with an EAF, where the sponge iron is introduced to achieve fusion and undergo further refining to produce steel. The shaft furnace method is the most used approach for this purpose. In this case, the reduction of iron occurs in the presence of gaseous reductants. The outputs of these processes are iron and water but not CO_2. This way of steel production needs much more electricity (overall 1.10 $\frac{\text{MWh}}{\text{t steel}}$) in comparison with the primary and secondary production and presupposes a continuous availability of hydrogen, which in case of Europe is difficult. The main factor to determine the amount of energy for steel production via HDR is the technology used to produce the hydrogen. If the overall demand for hydrogen is produced via electrolysis using renewable electricity, then the energy demanded for one ton of steel produced via hydrogen electrolysis and EAF is between 3.5 and 3.95 MWh. Whereas 75 % of this energy demand is required for hydrogen electrolyzer, meaning 2.63 - 2.96 MWh [49, 53, 54]. Assuming that the EU-27* manages to reduce the primary steel production, to re-use the steel, to improve the separation rate of copper and steel and to increase the recycling rate than a high level of circularity will be achieved. Figure 22 represents the production of steel at the current stage and its development in the future. It is to mention that the amount of primary steel produced in 2050 is forecasted to decrease while the production of secondary steel will increase. It also illustrates the difference between secondary steel production without eliminating the copper and the circular approach. In the first case, the amount forecasted for 2050 approx. double compared to the primary steel production. The y-axis represents the amount of steel produced in Mt [50].

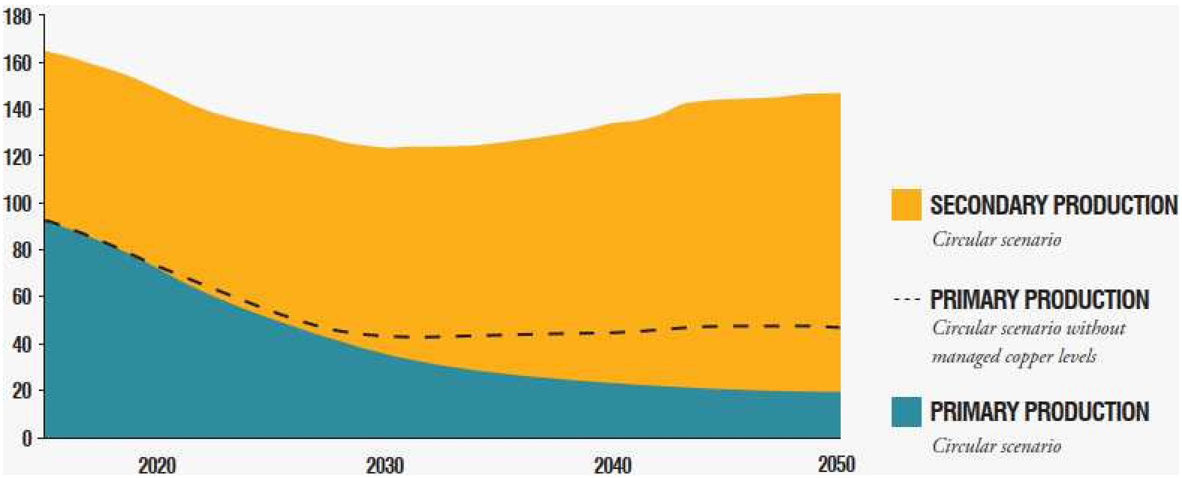

Figure 22: Steel production at status quo and the future development [50]

All these factors also influence the quality of the scrap which can be used again in the EAF process. Moreover, it is forecasted that the scrap will increase the share of its applications. Based on the prognosis stated in “Material Economics” [50] the amount and quality of scrap will increase covering by 2050 over 80 % of the EU steel demand. Figure 23 represents the evolution of steel production versus the increase in supply of the steel scrap [50].

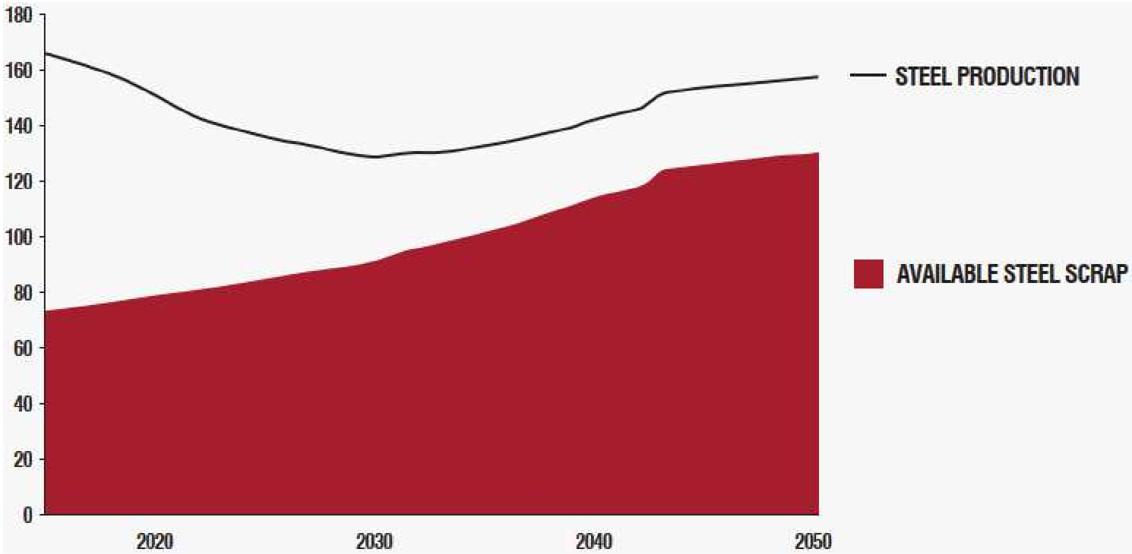

Figure 23: Future steel production vs. increase in steel scrap supply [50]

In order to determine the amount of energy demanded for the production of steel based on different routes once again Figure 22 is used as a reference. The reduction in primary steel production is apparent and, therefore, an additional assumption is made that the entire primary steel production is substituted with the HDR-Method. Given that Norway and Switzerland are not members of the European Union, further investigation was conducted. According to the World Steel Association's report [56] on Swiss steel production, the annual change rate of steel production was analyzed. The findings indicate that the steel capacity of Norway and Switzerland has remained constant over time. The entire steel production is based on the EAF Method. Norway's average steel production between 2009 and 2018 was 0.59 Mt, while Switzerland's average production was 1.5 Mt during the same period [56]. Based on past data, it is assumed that the steel capacity of these countries will not increase in the future. Consequently, the amount of secondary steel produced by Norway and Switzerland in 2050 is expected to remain constant at 0.59 Mt and 1.5 Mt, respectively. The total steel production in 2050, categorized by production method, is as follows:

- The quantity of primary steel produced in 2050 is 19 Mt.
- The quantity of secondary steel produced in 2050 is 136 Mt.

The final step involves determining the energy demand required to produce the aforementioned quantities of steel and distinguishing the energy carrier used, specifically electricity, and hydrogen. Notably, electricity is also required to produce steel via the HDR-Method. According to the assumption, which stipulates that the entire primary steel production in 2050 is based on the HDR-Method, the UED for steel production utilizing coal as an energy carrier is assumed to be zero. In 2050 the UED to produce 19 Mt via HDR-Method is forecasted to be 51 TWh which corresponds to 1.2 Mt H_2 and to produce 136 Mt via EAF is forecasted to be 130 TWh.

3.5 Exergy analysis of diverse applications.

The subsequent chapters address the computation of exergy requirements for various applications. As mentioned in Chapter 2, the determined values at the status quo are the foundation of the forecast. In the following paragraphs the UED of stationary engines, the UED for different process heat applications, the UED of the aviation and navigation sectors, the UED of the Lighting and ICTs, and the UED of the rail with and without powerlines are investigated. The demographic and economic development is based on the information presented in Methodology. In order to determine the UED certain conversion factors are mandatory therefore, their percentages are represented in Table 8. The values are provided by Exergy as Criteria for Efficient Energy Systems [7]. For certain technologies, the exergy and energy efficiency values are provided as ranges. This is based on the method used for their determination.

Table 8: Exergy and energy efficiencies of other final energy applications [7]

Technology	Useful Exergy [%]
Railway - Diesel	28 - 30
Railway - Electric	65 - 85
Aircraft	20 - 28
Ship - Diesel	15 - 30
Stationary Engines	50
Lighting - Halogen	12 - 15
Lighting - Fluorescent Lamp	24
Lighting - LEDs	42 - 49
BEV - Cars and LDT	74
Intern Combustion Engine - Cars and LDT	33
BEV - HDT	74
Intern Combustion Engine - HDT	33

3.5.1 Exergy Demand of stationary engines

The initial sector under examination is that of stationary engines. The FfE methodology identifies pumps, compressed air, and mechanical energy as belonging to this category. FfE also indicates that the only energy carrier for this sector is electricity. Currently, the FEC stands at 683 $\frac{\mathrm{TWh}}{\mathrm{a}}$. The technological development of stationary engines, namely the efficiency gain is expected to decline by -0.25 % per year, as mentioned by NEFI [12]. Considering the population and economic development combined with the technology progress a cumulative increase if 1.15 % annually is forecasted. As a result, by 2050, it is projected that the FEC will reach 974 $\frac{\mathrm{TWh}}{\mathrm{a}}$, Applying the exergy conversion factor of 0.5 as indicated in Table 8 an exergy demand of 487 $\frac{\mathrm{TWh}}{\mathrm{a}}$ is forecasted.

3.5.2 Heat demand

The methodology utilized for determining UED for this sector is based on Figure 2. Firstly, the FEC is determined. To gather the data in regard to the FEC the FfE database is utilized. FfE classifies the temperature levels into three categories. The first sequence is the processes operating at temperature levels till 100°C, followed by processes operating at temperature levels of 100 - 500°C, and processes operating at temperature levels higher than 500°C. The classification done by FfE does not suit the simulation parameters applied in this research. Therefore, the presented temperature levels were subsequently adjusted as follows in order to perform the simulation:

- 25°C,
- 80°C,
- 150 °C,
- 350°C,
- 1000°C.

The classification in these temperature levels is mandatory due to the fact that different sectors i.e., iron and steel or chemical and petrochemical operate in the higher temperature ranges, meaning > 1000°C whereas the pulp, paper, and print operate in the lower temperature ranges <100°C [7]. Subsequently, the exergy value of the analyzed technologies differs in accordance with the operating temperature. The classification of these temperature levels is depicted in Figure 24. To determine the exact split of the FEC in different temperature ranges the overall value provided by FfE namely 5726 $\frac{\mathrm{TWh}}{\mathrm{a}}$ was multiplied with the percentages indicated in Figure 24. The first interval indicated in Figure 24 accounts for 14.30 %, the second interval accounts for 9.50 %, the third interval 20.4 %, followed by 5.6 %

for the fourth interval, and lastly 49.80 for technologies operating at temperatures higher than 400°C.

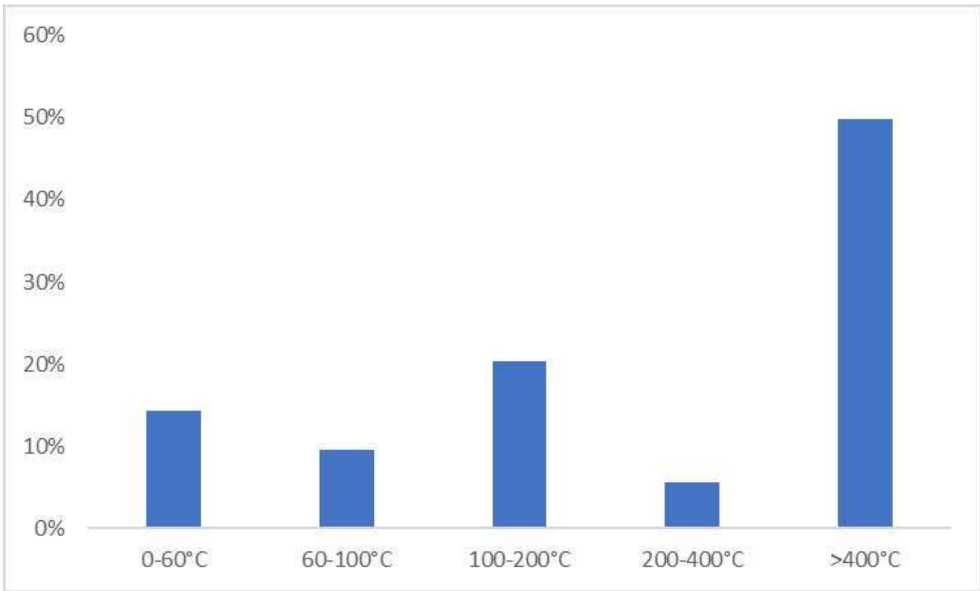

Figure 24: Classification of the process heat based on different temperature levels [57]

The next step consists in converting the FEC into UED. To determine the UED the values provided by FfE are multiplied by the corresponding percentages presented in Figure 24. Subsequently, Equation (2) is utilized considering that the $T_{Ambient}$ is 10 °C.

$$\text{UED} = \text{Heat Demand} * (1 - \frac{273{,}15 + \text{T}_{\text{Ambient}}}{273{,}15 + \text{T}_{\text{Heat Demand}}}) \quad (2)$$

Next step involves extrapolating the values obtained for each temperature level up to the year 2050. To enable such extrapolation, certain parameters have been postulated. On one hand, the thermal efficiency gain forecasted by NEFI [12] is assumed to exhibit a negative growth rate of -0.49 % annually. Considering the economic and demographic development a cumulative annual change of 0.87 % is forecasted. Table 9 presents the analyzed temperature ranges, the final energy consumption in 2019, and the forecasted values for 2050 in TWh. The calculation of the values is based on Equation (1). Based on the same table it is observed that the smaller the operating temperature, the higher are exergy losses. Comparing the UED based on different temperature levels is to observe that the UED the impact of the Carnot factor decreases, meaning that by increased operating temperatures the UED is higher.

Table 9: Useful exergy demand of the Heat processes for different levels for 2050

Temperature Level	FEC 2019	FEC 2050	UED 2050
25°C	819	1071	54
80°C	544	712	141
150°C	1168	1528	506
350°C	321	420	229
1000°C	2852	3730	2364

3.5.3 Transport demand for aviation and navigation

This chapter presents an analysis of the energy demand in the aviation and navigation sectors. The analytical approach follows the same procedure as in previous chapters.

3.5.3.1 Aviation

The EU's aviation sector is projected to experience growth over time, leading to a rise in the annual number of flights [58]. By 2050, it is estimated that there will be 16 million flights, representing a 1.7 % annual increase compared to the current state [58].

Initially, this study examines the energy demand of the aviation sector, beginning with an assessment of energy consumption in 2019 as a baseline. To determine this value, data from EUROSTAT was employed, which disclosed that the aviation sector consumed 79 $\frac{\mathrm{TWh}}{\mathrm{a}}$ of energy. According to a report by Eurocontrol [58], the growth of the aviation sector in Europe will not be homogeneous. The Eastern countries are anticipated to develop at a significantly faster pace compared to their Western counterparts.

The Base scenario is one of the three scenarios presented in EUROPEAN AVIATION IN 2040 Challenges of growth [58]. The choice of this scenario is justified by its assumption of a moderate development trajectory for Europe's GDP, CO_2 prices, and oil prices per barrel. In contrast, the other two scenarios assume either stronger or weaker growth in GDP and the aforementioned factors.

Considering the yearly growth rate of 1.7 % and the economic and demographic development [11, 41] of the EU, a combined growth rate of 3.06 % per year is anticipated. The aviation sectors of Switzerland and Norway were also considered [59]. Using this projection and applying Equation (1), the domestic aviation sector's UED for 2050, with an exergy conversion factor of 0.25 is forecasted to be 51 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

3.5.3.2 Navigation

The subsequent objective is to evaluate the development of domestic navigation. Maritime transport plays a pivotal role in the modern economy, In EU-27* the performance of the maritime sector is highly dominated by the countries located on the Rhine which accounts for 84 % of the overall maritime traffic. The overall transport of goods declined by 11 %, the reason being the low water levels [60]. Currently, long-chain hydrocarbon fuels are predominantly used in maritime transport, which are major contributors to greenhouse gas emissions. Maritime development is strongly dependent on the economic and demographical development of the EU-27*. In periods when the economy, namely the GDP rises, the overall performance of the maritime sector increases. The major developments in regard to the utilized technologies are automatization of processes, implementation of artificial intelligence, etc. [11, 41, 61]. The current energy consumption reported by EUROSTAT accounts for 63 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Considering the combined growth of 3.06 % per year and utilizing Equation (1) the forecasted result for 2050 considering the exergy conversion factor of 0.3 mentioned in Table 8 is 29 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

3.5.4 Exergy demand of LEDs and ICT

The present chapter aims to analyze the useful ED of two distinct categories, namely lighting including the following categories: LEDs, halogens, fluorescent lamps, and ICTs.

The FfE values are reported concerning to the phenomenon of lighting, encompassing all conceivable sources of lighting. Hence, the categorization of these values becomes imperative. In the absence of pertinent data concerning the percentage distribution on a European level, it is postulated that the percentage distribution is analogous to that of Austria. [7] Table 10 outlines the classification of these values into three principal categories:

Table 10: Percentage distribution of the main lighting categories [7]

Type	Distribution [%]
LED	28
Halogen	14
Fluorescent Lamp	58

The subsequent step involves determining the total FEC, utilizing the FfE database. The total FEC, which comprises lighting and ICTs, is 603 $\frac{\mathrm{TWh}}{\mathrm{a}}$ [62]. Subsequently, to determine the exergy utilized, various conversion factors, as outlined in Table 8, are applied to the lighting sector. It is assumed that 50 % of the overall electricity attributed to lighting and ICTs in certain sectors i.e., industry or services is used only for lighting. Moreover, the exergy efficiency of the ICTs is assumed to be 100 % due to the fact that the exergy is directly consumed and no conversion to useful energy is mandatory. The calculation for determining the exergy values for the lighting sector and ICTs is presented in

Table ***11*** The final step involves considering the demographic and economic growth in order to determine the UED in 2050 [11, 41]. Any possibilities of technological advancements in the future are not analyzed in this study. When considering all these parameters, it is determined that the development of lighting and ICTs will increase by 1.36 % annually

Table ***11*** indicates the UED for 2050 in TWh. The calculation was done based on Equation (1).

Table 11: Useful exergy demand of the LEDs and ICTs for 2050

Technology	FEC 2019	FEC 2050	UED 2050
LED	85	128	17
Halogen	42	64	1
Fluorescent Lamp	175	266	34
ICT	302	459	459

3.6 Rail with and without powerline

The following chapter deals with the development of rail transport and will distinguish between rail with and without power lines. Analyzing the current situation in the EU (David Briginshaw) it is stated that 60 % of all main lines are electrified. Furthermore, 80 % of all traffic is running on these lines. [63] Electrified rails represent an environmentally friendly mode of transport. Obviously, the countries in the EU have a different rates of electrification, Switzerland is the only country with a fully electrified system, whereas Lithuania has an electrification rate of 8 % [63, 64]. Overall, the trend in the rail sector is to electrify the remaining lines. From a technical point of view, there should not be any obstacles for further changes. [64] For the purpose of this analysis, it is assumed that the FEC as well as the UED for the rails without powerline remains the same as in 2019, and the rails with powerline will continuously gather a higher market share.

First of all, the FEC for status the quo is analyzed. The rail sector of Norway and Switzerland was gathered form the corresponding sources. Therefore, the national providers indicated a FEC for Norway of 0.60 $\frac{\mathrm{TWh}}{\mathrm{a}}$ for rails with powerline and 0.2 $\frac{\mathrm{TWh}}{\mathrm{a}}$ for rails without powerline, and since Switzerland is fully electrified an FEC of 1.8 $\frac{\mathrm{TWh}}{\mathrm{a}}$. [65, 66] Based on the data provided by EUROSTAT in EU the FEC of the rail sector overall constitutes 64 $\frac{\mathrm{TWh}}{\mathrm{a}}$. The rails with powerlines use 49 $\frac{\mathrm{TWh}}{\mathrm{a}}$ and the trains without powerlines use 15 $\frac{\mathrm{TWh}}{\mathrm{a}}$ [65].

The second step is to consider the population growth and the economic growth of the EU-27* described in the Methodology. Furthermore, the exergy conversion factor from the final energy is considered. The values are indicated in Table 8. For the rails with powerline, a conversion factor of 0.8 is considered and for the rails without powerline a factor of 0.3. Based on the presented information and the forecast for 2050 Table 12 illustrates the UED of the rail sector in 2050 in TWh. The extrapolation was done based on Equation (1).

Table 12: Useful Exergy demand of rail sector in 2050

Means of transport	FEC 2019	FEC 2050	UED 2050
Rail with powerline	49	75	60
Rail without powerline	15	15	4

4 Results and Discussion

In this chapter, the results of scenario 1 and scenario 2 are presented and discussed. As already mentioned in Chapter 3.1, the reason for choosing these two scenarios is that scenario 1 stands for the constant development of the RES, and scenario 2 represents the maximum development of the RES. Therefore, the results of the simulation represent two different case studies of the future exergy system. The differences between the results are analyzed in the following paragraphs. Due to the fact that the current energy system is complex and based on the technological development in the course of the energy transition, it was decided to classify the results into four main categories:

1. primary exergy,
2. electricity,
3. gas,
4. the heating grid at low and medium-temperature levels.

The differentiation between low and medium-temperature levels is based on the fact that the excess heat of different applications is used on the one hand to supply the low-temperature grid which is operating at 34°C and on the other hand to rise the temperature from low to medium-temperatures which is operating at 90°C. From an exergetic, this classification increases the efficiency of the system. This phenomenon is in the following paragraphs also discussed. The interpretation of the results is based on daily mean values as it is indicated in the following plots.

4.1 Primary exergy scenario 1

According to Figure 25, the exergy-optimized system of the EU in 2050 will be primarily composed of hydrogen imports, accounting for 46 %, and Synthetic natural gas (SNG) imports, constituting 26 %. In terms of renewable energy generation within the EU, wind power emerges as the dominant source, contributing to 2708 $\frac{\mathrm{TWh}}{\mathrm{a}}$, equivalent to 73 % compared to 432 TWh in 2019. This is followed by photovoltaic generation with an annual production of 678 TWh, compared to 137 TWh in 2019, and hydropower generation producing 342 $\frac{\mathrm{TWh}}{\mathrm{a}}$ compared to 348 TWh in 2019 and lastly biomass generated energy accounts for 1850 $\frac{\mathrm{TWh}}{\mathrm{a}}$ compared to 199 TWh in 2019 [67] The presented percentage differences in comparison to status quo are discussed in the further paragraphs.

Comparing the primary exergy demand in 2019 with the minimum primary exergy demand in 2050 a theoretically exploitable gap of 12290 $\frac{\mathrm{TWh}}{\mathrm{a}}$ is determined. On the other side, the amount of energy generated through renewable sources increases by 68 %. Also, it is to mention that based on this scenario the EU is strongly dependent on gas imports. This scenario forecasts 11123 TWh of gas imports equivalent to an increase by 178 % compared to 2019.

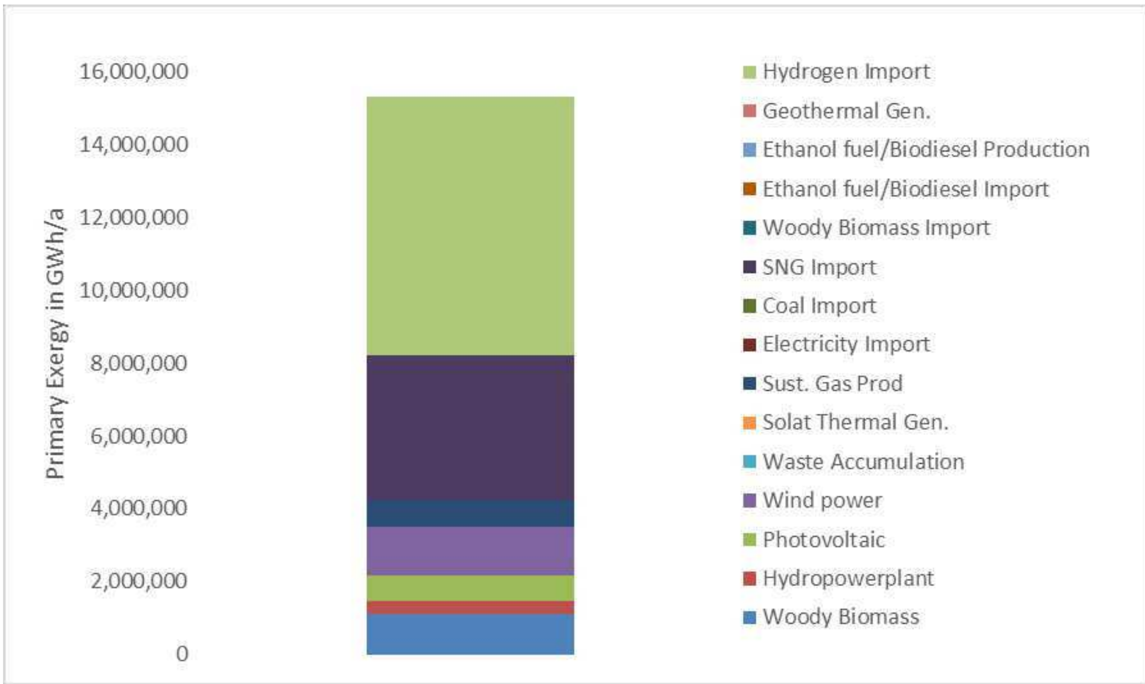

Figure 25: Primary exergy based on scenario 1

4.2 Electricity scenario 1

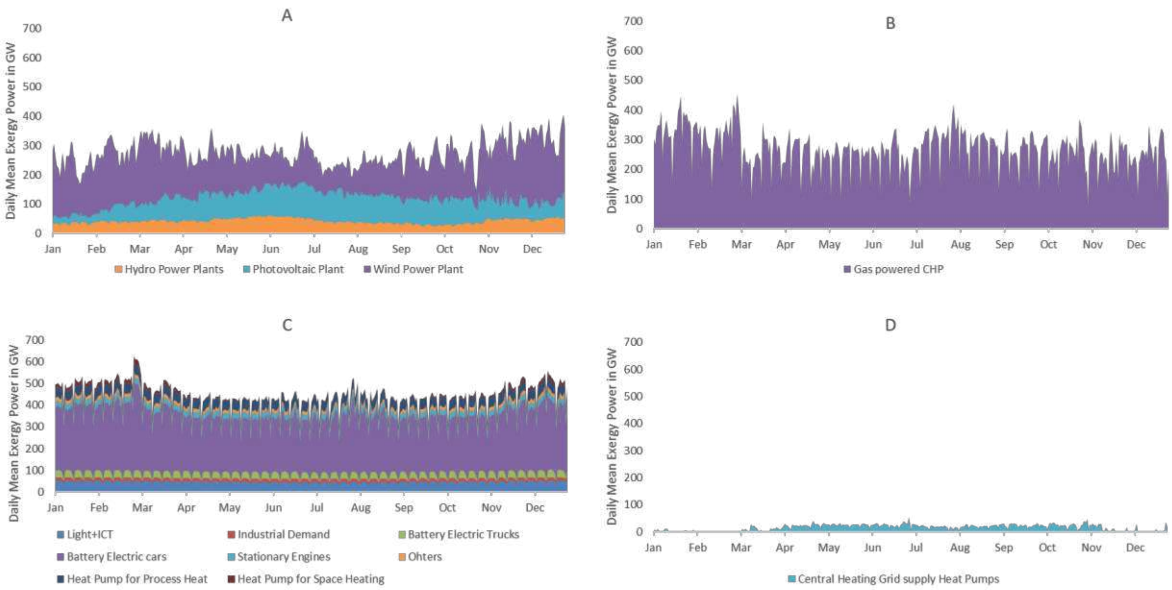

Figure 26: Renewable generation (A), Controllable power generation (B), Final electricity usage (C) and Other electricity applications (D) scenario 1

Figure 26 A shows that the generation of electricity through renewable sources is mainly dominated by wind power. This type of energy generation reaches peaks of up to 400 GW and experiences a seasonal development with increased production beginning in late October and continuing till April. Conversely, photovoltaic power generation is a more seasonal type of energy production, with more energy being produced during periods of greater sunlight. The highest amount of power is produced in July, reaching 110 GW. Lastly, hydropower generation is the most consistently produced energy source throughout the year, with an average production of 60 GW. Over the analyzed period of time the wind power plant, the hydropower plants and, the photovoltaic systems generated 2406 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

An analysis of traditional power generation indicates that the only exergy provided over the considered year is based on gas-powered Combined heat and power (CHP). Figure 26 B shows that CHP power generation reaches spikes of 460 GW. Furthermore, there is no storage discharge since no excess exergy is stored during the year. Figure 26 C illustrates the typical course of the bathtub curve. It also shows that final electricity consumption peaks during the cold season, with the end of February, and that with the beginning of March a peak power of approx. 600 GW is reached. The spike is due to the increased usage of heat pumps during the colder periods of the year. Additionally, it should be noted that the controllable power generation is connected to the input values used in the simulation. Consequently, if we take into account factors such as waste accumulation, the outcomes will differ. However, it is important to highlight that waste accumulation primarily affects the quantity of imported gas and does not significantly influence the entire system.Comparing the final electricity usage of the EU-27* at status quo with the exergy-optimized results reveals a 64 % increase. Residual loads arise due to the trend of installing more renewable sources, which causes the production to vary. The residual loads in the EU do not exhibit significant frequency changes between negative to positive loads. The residual load remains positive for the most extended period, with 96 % of the days exhibiting positive residual loads. The negative residual loads are balanced by connecting the electrolyze systems to the grid. Figure 26 D indicates that no electrolysis takes place during the entire year and at the same time illustrates that 138 $\frac{\mathrm{TWh}}{\mathrm{a}}$ are used for other purposes namely, to supply the heating grid which subsequently supplies the heat pumps. The heat pumps increase the temperature up to 150°C. The central heating grid is necessary to warm up buildings and homes as well as commercial places. (Chapter 4.4)

An in-depth analysis of the transportation sector's electricity usage indicates a heavy reliance on electrified systems. Electric locomotives contribute 60 $\frac{\mathrm{TWh}}{\mathrm{a}}$, while BEVs account for 2603 TWh per year. Stationary engines require 195 $\frac{\mathrm{TWh}}{\mathrm{a}}$, while compressors require 61 $\frac{\mathrm{TWh}}{\mathrm{a}}$ under this circumstance. In addition, ICT systems demand 459 TWh annually, while lighting systems require 402 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

Figure 27 illustrates the yearly development of the batteries in the households and the pumped storage. Due to the fact that the simulation chooses which technologies are best suited to achieve the highest efficiency, in this analyzed case the pumped storage for the seasonal transition as well as the short time storage of the photovoltaic technologies are almost not taken into consideration. The pumped storage is the entire year fully charged and ready to provide 250 GW daily. and the household batteries which store the electricity produced via photovoltaic systems illustrate slight changes in their value, which does not have any impact on the overall European system.

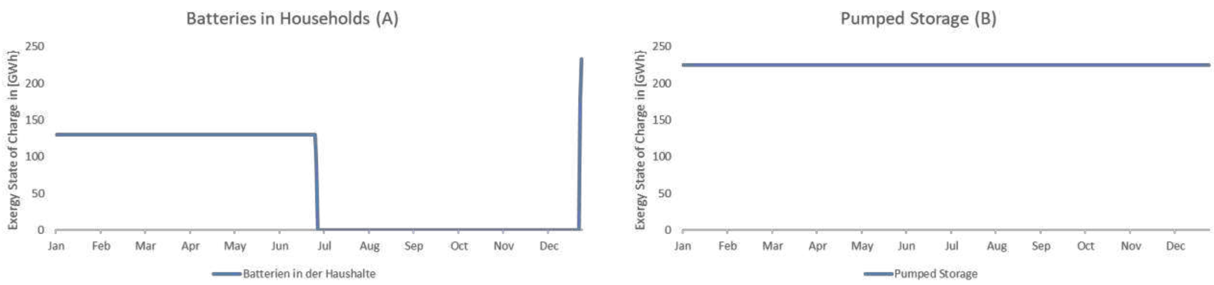

Figure 27: Batteries in households (A) and Pumped storage (B) scenario 1

4.3 Gas scenario 1

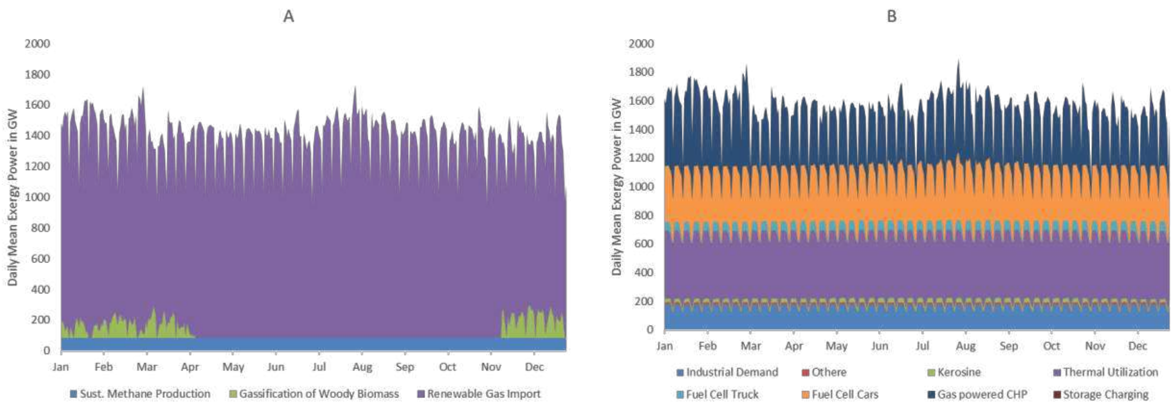

Figure 28: Gas supply (A) and Gas usage (B) scenario 1

Figure 28 illustrates on the left side the gas supply and on the right side the gas demand in an optimized scenario. Taking a closer look at Figure 28 B is to distinguish that the main usage of the gas in an exergy-optimized way is to use the chemical energy for the purpose of providing high-temperature thermal energy for CHP plants and for the demand in the industrial sector. It is also applied in the transport sector. The illustration indicates that the usage of fuel cell cars over the analyzed period features a constant periodicity reaching a consumption of approx. 400 $\frac{\mathrm{GW}}{\mathrm{day}}$. Fuel cell drives such as fuel cell locomotives, fuel cell ships, and fuel cell cars demand 4 $\frac{\mathrm{TWh}}{\mathrm{a}}$, 29 $\frac{\mathrm{TWh}}{\mathrm{a}}$, and 1168 $\frac{\mathrm{TWh}}{\mathrm{a}}$, respectively, for navigation purposes and land transportation.

Figure 28 A illustrates that from April to November the most efficient way to supply the needs of the population is to import renewable gas due to the moderate consumption from November until April where the gas consumption increases because the production of gas via woody biomass acts as a supplement. If closely analyzing Figure 28 A indicates that the total amount of gas imported in 2050 constitutes 11123 TWh. [68]. The reason for this increase in gas imports is on the one hand due to the assumptions made in the industry sectors, the applied technological developments as well as the limited renewable expansion. The overall sustainable methane production remains constant as due to a fix time series over the entire year, as mentioned in Chapter 2 andreaches a production of 740 TWh which represents 6 % of the entire supply.

The biomass gasification finds its application in thermal processes. It accounts for approx. 11.5 % of the overall production.It is also observed that the main usage basically 90 % of the biomass gasification is for the operation of the CHP plants which demonstrates that the increased production in March and April and in the wintertime is due to the increased final electricity usage (Figure 26 C).

Figure 28 B indicates the way the supplied gas is used. The gas-powered CHP plants constitute the highest amount reaching 3670 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Approx. 6 % of the entire usage is applied for the storage of excess heat at medium-temperatures. From the entire thermal utilization, 75 % is due to the application of SNG at 1000°C, 13 % is due to the thermal utilization of hydrogen at 1000°C, and 12 % is due to the thermal utilization of SNG at 350°C.

4.4 Heat scenario 1

In the following chapter the optimized heat sector of the EU-27* is analyzed, and certain recognitions are described. The two main categories analyzed are:

1. the heating grid supply and demand
2. storage at low-temperatures and at medium-temperatures.

4.4.1 Heat supply, demand, and storage at low-temperatures

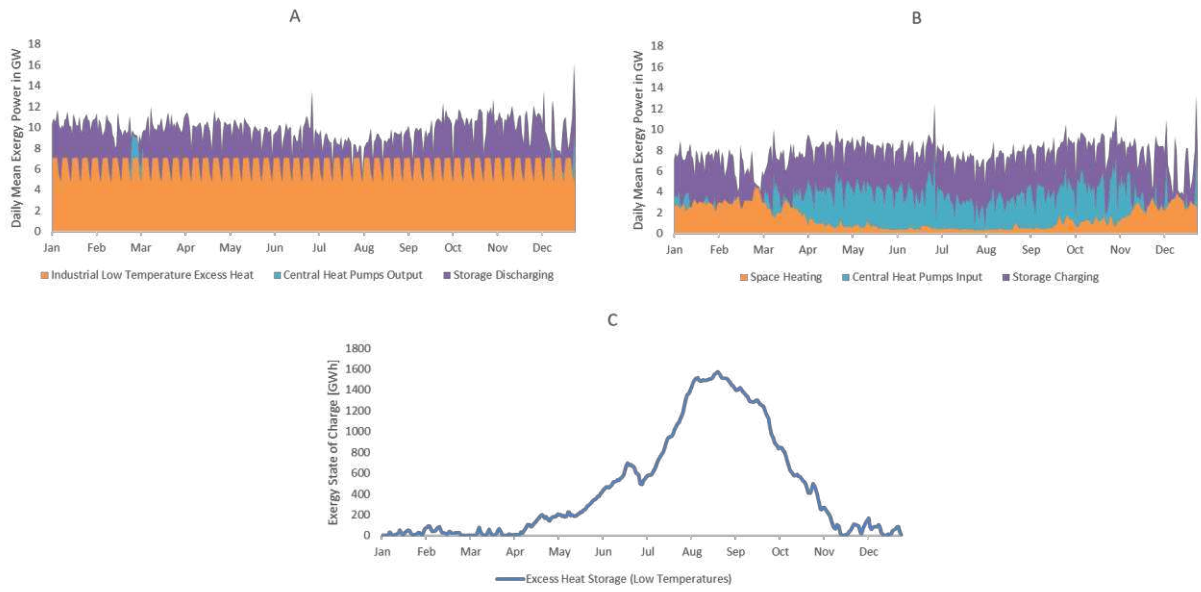

Figure 29: Heating grid supply LowT (A), Heating grid usage LowT (B) and Excess heat storage LowT (C) scenario 1

The low-temperature heating grid is a key component of a sustainable and efficient heating system. To better understand its functioning, Figure 29 illustrates the supply, demand, and storage of the low-temperature heating grid.

As shown in Figure 29 A, the low-temperature grid is mainly supplied by the low-temperature excess heat which accounts for 57 $\frac{\mathrm{TWh}}{\mathrm{a}}$,equivalent to 67 % from the entire supply. The rest of the low-temperature heat is provided directly by the centralized heating grid supplying the heat pumps. Figure 29 B highlights certain seasonal changes that are apparent in the system. During the cold periods of the year, space heating is the primary source of demand, resulting in a typical bathtub-profile accounting for 20 % or 13 $\frac{\mathrm{TWh}}{\mathrm{a}}$ of the overall low-temperature demand. In the warm period of the year when the space heating demand is low the energy is firstly lifted to the medium-temperature grid and in a subsequent step is again heated up to 150°C. In contrast, the central heat pump presented in Figure 29 A increases the working temperature from the ambient level to 32.5°C. On the other side, the central heat pump illustrated in Figure 29 B has the purpose to increase the operating temperature to 90°C. As Figure 29 B illustrates the central heat pump input demand more energy during the warm periods of the year, starting in May and continuing through November, and find its usage in supplying the medium-temperature heating grid. The demand for this purpose consists of $20\,\frac{\mathrm{TWh}}{\mathrm{a}}$.

In order to optimize the system, it is essential to store excess energy during the warm periods of the year. Figure 29 C represents this energy storage, which is used to meet the demand of the central heat pumps. Figure 29 B reveals that the heat storages have a significant increase in the amount stored starting at the end of April and continuing through the beginning of winter. The amount of heat stored over the entire year is $3972\,\frac{\mathrm{TWh}}{\mathrm{a}}$.

It is also important to mention that the low-temperature excess heat is stored for a longer period. The reason is that on the one hand at lower temperatures the conversion losses are smaller and on the other hand the low-temperature storage is used to store the energy for a seasonal shift, i.e., from summer to winter.

4.4.2 Heat supply, demand, and storage at medium-temperatures

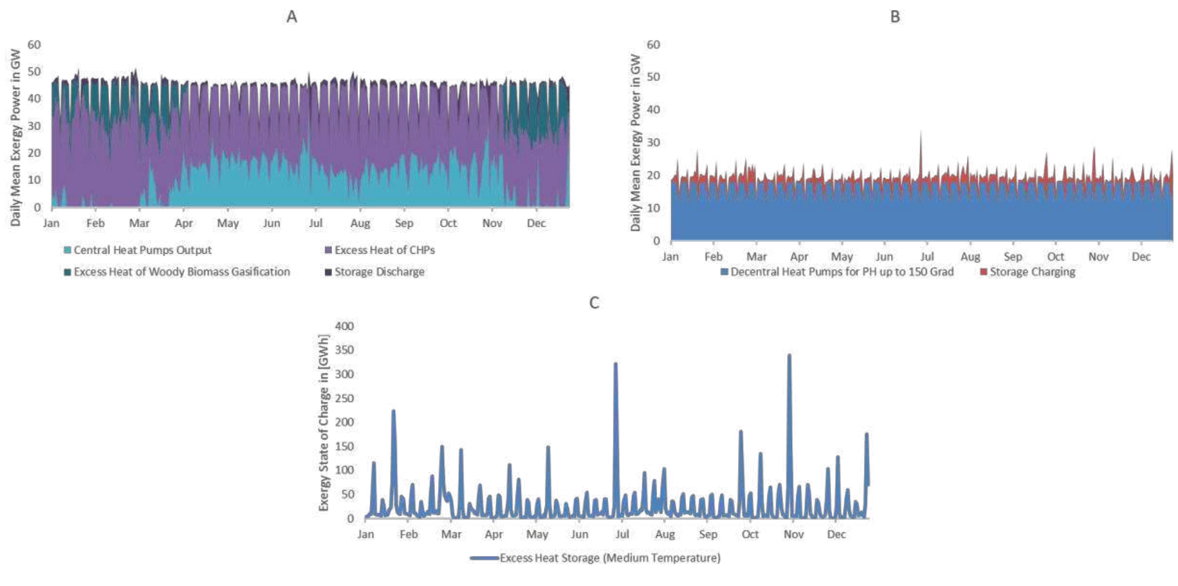

Figure 30: Heating grid supply MedT (A), Heating grid usage MedT (B) and Excess heat storage MedT (C) scenario 1

Figure 30 represents the heating grid supply, demand, and storage at medium-temperatures. The medium-temperature heating grid as illustrated in Figure 30 A is supplied through various technologies i.e., the excess heat of the woody biomass gasification and excess heat of the gas-powered CHP plants. The gasification of woody biomass accounts for $40\,\frac{\mathrm{TWh}}{\mathrm{a}}$ and the gas-powered CHP plants account for $233\,\frac{\mathrm{TWh}}{\mathrm{a}}$. The excess heat from woody biomass gasification occurs at a temperature of 92°C. The medium-temperature heating grid is subsequently used as an input for the decentralized heating pumps in order to cover the process heat demand at 150°C in industry. The heat demand at 150°C accounts for 146 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

Figure 30 C illustrates the high periodicities of the stored heat, which occurs due to the fact that the supply from different conversion units is required over a shorter period of time to meet the demands of industrial process heat. As a result, medium-temperature excess heat storage are mainly used for short-term buffers, and it constitutes 217 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

4.5 Interpretation of the results - scenario 1

The results of scenario 1 indicate that the amount of electricity generated through the RES is not sufficient to cover the electricity demand. The amount of electricity produced with the RES accounts for 2406 $\frac{\mathrm{TWh}}{\mathrm{a}}$ while the final electricity usage demands 3932 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Therefore, more gas imports are necessary. In scenario 1 the gas import constitutes 11123 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Subsequently, this gas is used to supply the gas-powered CHP which are connected continuously to the grid and supply the deficit. Analyzing the final electricity usage is presented that the BEV has a high impact on the system. From an exergy standpoint, it is efficient to switch to technologies that demand electricity or gas as energy carriers because electrical energy as well as the chemical energy have an exergy share of approx. 100 %. [8] Analyzing the future energy system based on scenario 1 is to observe the transition in this direction. The oemof simulation indicates that one of the highest shares in the final electricity usage constitutes the BEV accounting for 2378 $\frac{\mathrm{TWh}}{\mathrm{a}}$ and on the other side the fuel cell cars demand 1168$\frac{\mathrm{TWh}}{\mathrm{a}}$. Another realization is that the modeling results indicate a transition to a higher share of heat pumps. By using the heat pumps the overall efficiency of the system increases. The efficiency of the heat pumps is determined by the coefficient of performance. Subsequently, the temperature difference between the heat input and heat output is crucial. The smaller the difference between these temperature levels is, the higher the coefficient of performance. This technology reaches efficiencies of up to 700 %. [8] This means that specific grids are necessary to cover the demands of a low-temperature i.e., 34°C, and other grids cover the demand by 90°C. Because of insufficient generation from RES the share of excess heat generated by the gas-powered CHP plant for the supply of the medium-temperature grid accounts for 10 %. Optimizing the system using excess heat and heat pumps, it is created an efficient and sustainable energy system. In this way, the exergy losses are reduced.

4.6 Primary exergy scenario 2

Figure 31 illustrates the primary exergy associated with scenario 2, showcasing a more progressive outlook. Notably, the share of wind power, photovoltaic, and hydropower in this scenario exceeds that of scenario 1 by 195 %, 64 %, and 12 % respectively. Additionally, it is evident that the highest exergy demand is attributed to the import of hydrogen and SNG. In terms of hydrogen import, a reduction of 33 % is observed in this scenario, while the import of SNG experiences a decrease of approximately 12 %. Likewise, in alignment with the first scenario, wind power emerges as the dominant energy generation method, accounting for 4006 $\frac{\mathrm{TWh}}{\mathrm{a}}$ compared to 432 TWh in 2019, followed by photovoltaic systems generating 1108 $\frac{\mathrm{TWh}}{\mathrm{a}}$ compared to 137 TWh in 2019, biomass contributing 710 $\frac{\mathrm{TWh}}{\mathrm{a}}$ compared to 199 TWh in 2019, and hydropower yielding 415 $\frac{\mathrm{TWh}}{\mathrm{a}}$ compared to 348 TWh in 2019 [67]. A comparative analysis of the current state of affairs reveals a theoretically exploitable gap of approx. 4000 $\frac{\mathrm{TWh}}{\mathrm{a}}$ for the minimum primary exergy demand, equivalent to 23 % indicating an increased efficiency of the exergy usage. Notably, according to this scenario, the EU remains reliant on gas imports, which amounts to 8293 $\frac{\mathrm{TWh}}{\mathrm{a}}$, signifying a 107 % increase compared to the figures recorded in 2019 [67, 68]. The presented percentage differences in comparison to the status quo are discussed in the further paragraphs.

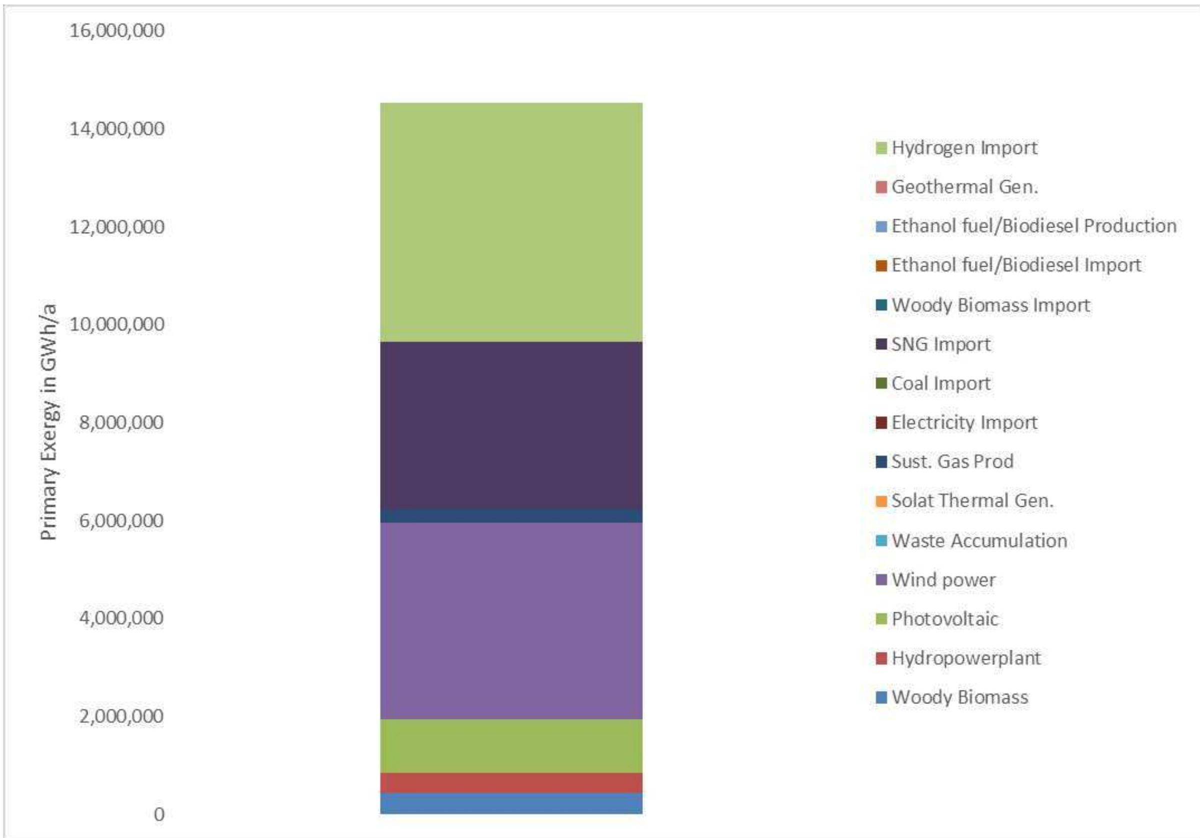

Figure 31: Primary exergy based on scenario 2

4.7 Electricity scenario 2

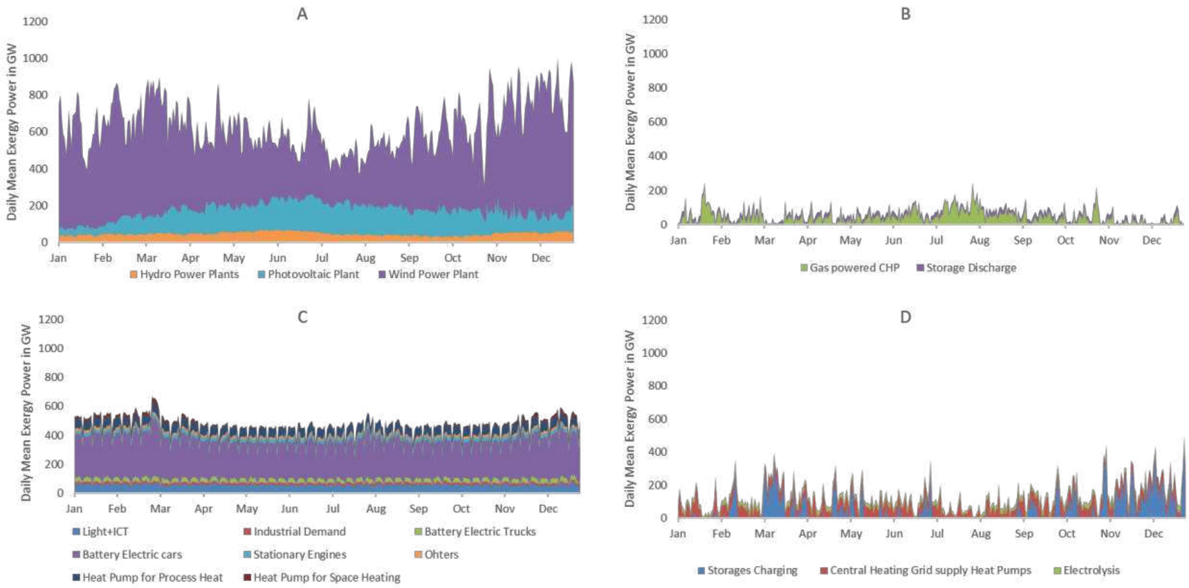

Figure 32: Renewable generation (A), Controllable power generation (B), Final electricity usage (C) and Other electricity applications (D) scenario 2

Figure 32 A illustrates that the generation of electricity by renewables sources is mainly dominated by wind power. This type of energy production experiences a seasonal development with increased production beginning in late October and continuing till April. The peak production occurs in mid-December reaching almost 900 GW. Figure 32 A also shows how in times of low wind power generation the photovoltaic systems gain in strength and balance the overall production. Solar power generation is predominantly in the summer times of the year. The peak production is at the end of June and beginning of July and reaches 200 peaks at 200 GW. Hydropower generates electricity constantly throughout the entire year with an average of 50 GW. The overall generation of the RES constitutes 5529 $\frac{\text{TWh}}{\text{a}}$.

Figure 32 B illustrates the controllable power generation. Comparing the graph with Figure 26 B is to mention that in this case the gas-powered CHP plants only function as support power generation for the renewables meaning in periods of the year where the wind power generation drops and the amount of energy produced via photovoltaic systems and hydropower plants are insufficient to cover the entire demand the gas-powered CHP plants are connected to the grid and supply the existing needs. The overall production of the gas-powered CHP plants is 370 $\frac{\text{TWh}}{\text{a}}$. The overlap of both types of power generation is represented in Figure 33.

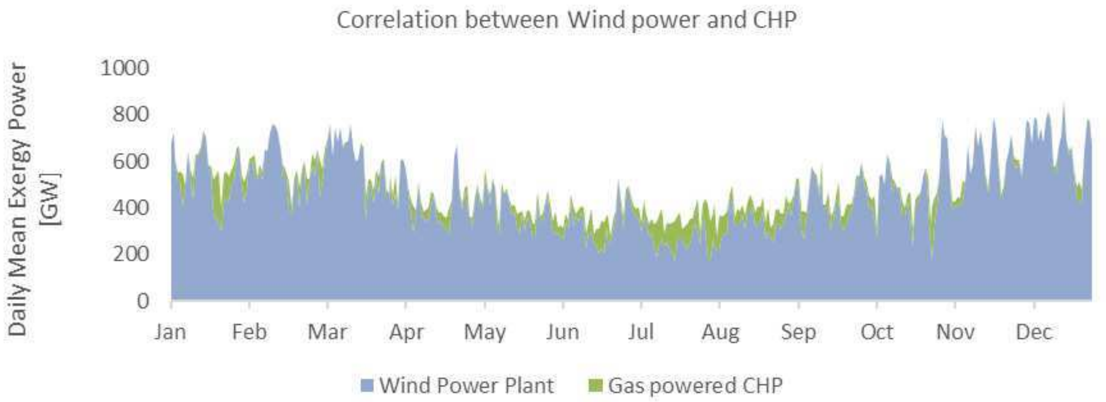

Figure 33: Correlation between wind power generation and gas-powered CHP plants scenario 2

Figure 32 C illustrates the typical course of the bathtub curve. The reason is the usage of the heat pumps for the space heating. Throughout the entire year, space heating undergoes seasonal fluctuations. For instance, during cold periods like February, there is a demand on average for 30 GW daily, whereas in the summer, the demand decreases to 5 GW daily. The overall heat usage for the space heating sector constitutes 108 $\frac{\text{TWh}}{\text{a}}$. It also shows that final electricity consumption peaks during the cold season, with the end of February and beginning of March indicating a peak power of approx. 700 GW during this period. As mentioned above, the controllable power generation is interlinked with the input values for the simulation, therefore, in the case when i.e., the combustion of waste accumulation is considered then other results will be provided. Whereas considering that waste accumulation will only impact the amount of gas that will be imported and will not have a major impact on the overall system. Whereas considering the waste accumulation will only impact the amount of gas that will be imported. Comparing the final electricity usage of the EU-27* at status quo with the exergy-optimized results reveals a 68 % increase. Residual loads arise due to the trend of installing more renewable sources, which causes the production to vary. In this scenario, the residual load exhibits significant frequencies in the change between positive and negative values. To balance the negative residual load's electrolysis is used and to balance the positive residual load the gas-powered CHP plants are deployed. Due to high periodicities caused by the negative residual loads, the electrolysis runs the entire year accounting for 196 $\frac{\mathrm{TWh}}{\mathrm{a}}$ and the CHP plants account for 370 $\frac{\mathrm{TWh}}{\mathrm{a}}$. An in-depth analysis of the transportation sector's electricity usage indicates a heavy reliance on electrified systems. Electric locomotives contribute 60 $\frac{\mathrm{TWh}}{\mathrm{a}}$, while BEVs account for 2603 $\frac{\mathrm{TWh}}{\mathrm{a}}$. In addition, ICT systems demand 459 TWh annually, while lighting systems require 402 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

Figure 32 D indicates on one hand, that the storages are charged in periods of increased production and lack of consumption. The periods when the storages are charged is interlinked with the amount of electricity produced via wind turbines. The amount stored over the considered year is 459 TWh while the overall capacity is 2194 $\frac{\mathrm{TWh}}{\mathrm{a}}$. The same figure indicates that the heat pumps of the low-temperature heating are supplied with electricity which amounts to 73 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Figure 32 D represents the usage of electrolysis as well in order to balance on one hand the negative residual loads in the energy system and on the other hand to produce H_2-gas.

Figure 34 indicates the deployment of household batteries and pumped storage. Household batteries illustrated in Figure 34 A are basically used for short-term purposes and act as a buffer to store the excess electricity. The storage occurs in periods of increased production and less demand i.e., July. The household batteries experience a high periodicity and frequent complete discharges. The pump storages are supplied through the excess electricity generated by the wind power plants. In this scenario the share of renewable energy generation is greater compared to scenario 1 therefore negative residual loads arise. Subsequently, the electrolyze takes place and the production of H_2 occurs as indicated in Figure 32 D. If Figure 34 B is compared to Figure 27 B is to mention that based on this scenario the optimizer decided first of all to use the pumped storage and therefore support the system and on the other hand decided to operate the pumped storage at a higher frequency. This indicates that in a progressive scenario, a surplus of electricity is expected to be generated and therefore the oemof model manages it more efficiently because the potential energy of the pumped storage represents 100 % exergy. A closer look at the periods of the year in which the CHP plants are connected to the grid matches the periods when the pump storages are empty, and no charging occurs.

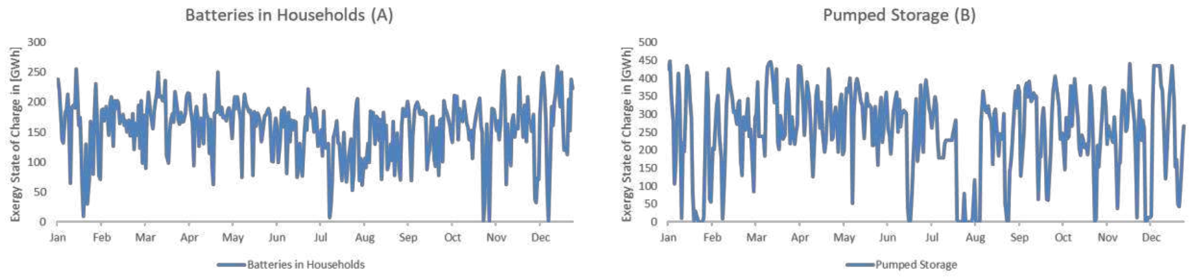

Figure 34: Batteries in households (A) and Pumped storage (B) scenario 2

4.8 Gas scenario 2

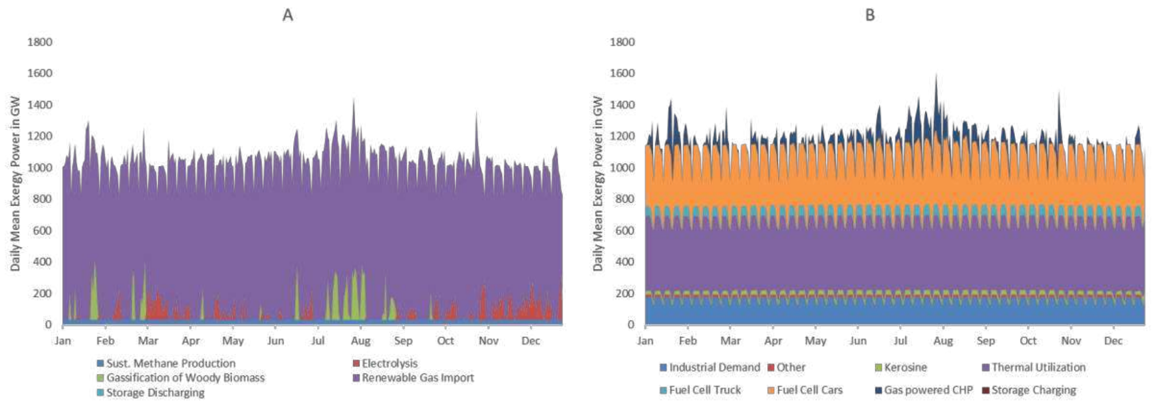

Figure 35: Gas supply (A) and Gas usage (B) scenario 2

Figure 35 illustrates on the left side the gas supply and on the right side the gas demand in an optimized scenario. As mentioned above the highest amount of energy used is the renewable gas import which accounts for 8294 $\frac{\mathrm{TWh}}{\mathrm{a}}$. In contrast to Figure 28 where the electrolysis does not take place, in this scenario H_2 is produced within the EU boundaries and accounts for 298 $\frac{\mathrm{TWh}}{\mathrm{a}}$. The gasification of woody biomass produces 239 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Combining these two technologies correspond to approx. 6 % of the overall gas supply. The production of sustainable methane is constant as due to a fix time series over the entire year, as mentioned in Chapter 2 and accounts for 284 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Figure 35 A also indicates that the production of gas via woody biomass gasification is not as efficient as the import of gas in the form of hydrogen or SNG through pipelines for other countries.

Taking a closer look at Figure 35 B is to distinguish that the main usage of the gas in an exergy-optimized way is to use the chemical energy for the purpose of providing high-temperature thermal energy for the CHP plant and also for the demand in the industrial sector. Furthermore, it finds application in the transport sector as well. Based on Figure 35 B the exergy used for the traction of the fuel cell cars was determined. The fuel cell cars demand on average 460 $\frac{\mathrm{GW}}{\mathrm{day}}$. For navigation and land transportation purposes the fuel cell locomotives, fuel cell ships, and fuel cell cars demand 4 $\frac{\mathrm{TWh}}{\mathrm{a}}$, 29 $\frac{\mathrm{TWh}}{\mathrm{a}}$, and 1168 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Fuel cells are used to address the limited range of batteries. Based on the simulation the most efficient way does not take into consideration the charging of the gas storage. In 2019 in the EU approx. 1000 TWh were stored. [69] A closer look at the gas-powered CHP plants and their usage indicates that from 580 $\frac{\mathrm{TWh}}{\mathrm{a}}$ 60 % are used to supply the heating grid at medium-temperatures. From the entire thermal utilization, 51 % is due to the application of SNG at 1000°C, 37 % is due to the thermal utilization of hydrogen at 1000°C, and 12 % is due to thermal utilization of SNG at 350°C.

4.9 Heat scenario 2

Similar to previous chapters, the heat supply, demand as well as the storage usage of the low-temperature and medium-temperature heating grids are analyzed.

4.9.1 Heat supply, demand, and storage at low-temperatures

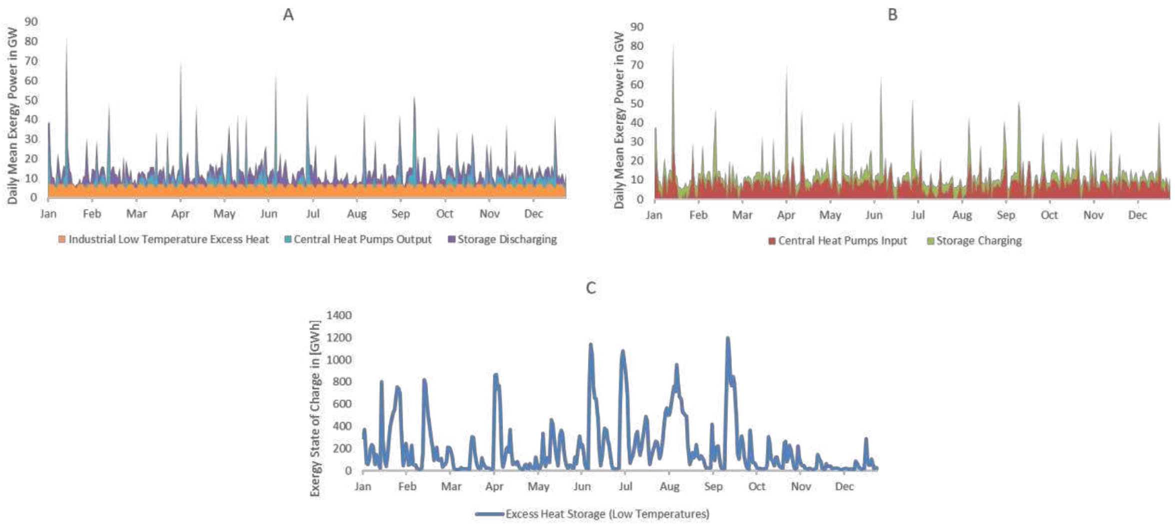

Figure 36: Heating grid supply LowT (A), Heating grid usage LowT (B) and Excess heat storage LowT (C) scenario 2

Figure 36 A indicates that the low-temperature excess heat supplies the baseload with 57 $\frac{\mathrm{TWh}}{\mathrm{a}}$ accounting for 67 %. Additional heat is provided by heat pumps which are supplied with electricity as indicated in Figure 32 D. The amount supplied via heat pumps is 30 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Since the heat is stored in periods of increased availability of excess heat which occurs in mid-January, April, and mid-Jun it can be then reused in periods of reduced production which is indicated in Figure 36 A. The amount of heat stored is 48 $\frac{\mathrm{TWh}}{\mathrm{a}}$. From an exergetic point of view the higher the temperature difference between the operating temperature and the ambient temperature, the higher the exergy losses. In this regard, it is more efficient to use the exergy provided by the low-temperature heating grid in order to cover the demand in the medium-temperature heating grid. The amount of exergy used for the space heating is not illustrated in Figure 36 B because the optimizer calculated that the most efficient way for this sector is through decentral heat pumps as described in Electricity scenario 2.

The output of the central heat pump supply is used to increase the ambient temperature to 32.5 °C. On the other hand, the input of the central heat pumps is used to supply the medium-temperature heating grid in order to increase the working temperature from 32.5 °C to 90 °C.

Figure 36 C indicates the way the excess heat is stored at low-temperatures. The heat is stored over short periods of time which indicates a high periodicity of their usage. The short terms storage act in this case as buffers to support the entire system and to provide heat when it is needed. The storages are being charged due to the central heat pump inputs. The high periodicity is also given due to the small conversion losses by low-temperatures. The low-temperature excess heat possesses a storage capacity of 1769 $\frac{\mathrm{TWh}}{\mathrm{a}}$.

4.9.2 Heat supply, demand, and storage at medium-temperatures

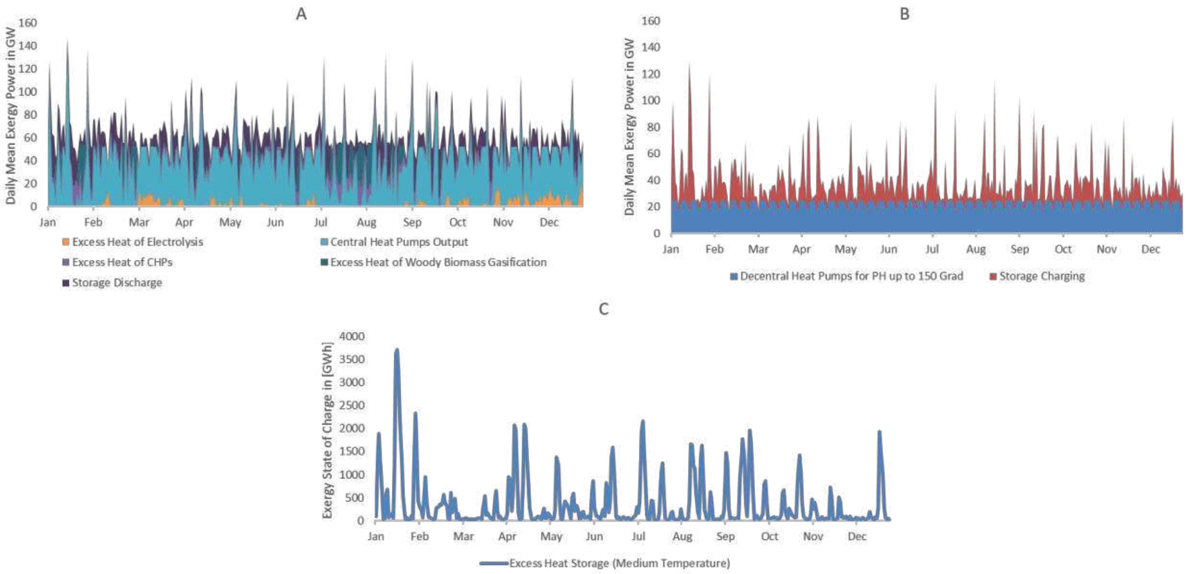

Figure 37: Heating grid supply MedT (A), Heating grid usage MedT (B) and Excess heat storage MedT (C) scenario 2

In the current optimized system, the production of gas via gasification of woody biomass, the use of gas-powered CHP plants, and the electrolysis excess heat has a major impact on the medium-temperature heating grid, as illustrated in Figure 37 A. The gasification of woody biomass supplies the medium-temperature grid with heat accounting for 28 $\frac{\mathrm{TWh}}{\mathrm{a}}$. Simultaneously, the gas-powered CHP plants also supply the medium-temperature grid with

37 $\frac{\text{TWh}}{\text{a}}$ heat. The excess heat of the electrolysis which occurs occasionally over the entire year accounts for 21 $\frac{\text{TWh}}{\text{a}}$. It is also important to mention that the medium-temperature grid is used to supply the decentral heat pumps in order to increase the working temperature up to 150°C. This type of heat pump finds its application in the industry sector. Figure 37 B indicates that over the entire year in periods of increased production, the heat is stored at 90°C in order to be used later.

Figure 37 C illustrates the high periodicities of the stored heat, which is due to the fact that the supply from different conversion units is required over a shorter period of time to meet the demands of industrial process heat. As a result, medium-temperature excess heat storage are mainly used for short-term buffers and have a storage capacity of 3169 $\frac{\text{TWh}}{\text{a}}$.

4.10 Interpretation of the results - scenario 2

The results of scenario 2 indicate that the amount of electricity generated through the RES exceeds the demand side. Based on Figure 32 the amount of electricity generated from the RES is 5530 $\frac{\text{TWh}}{\text{a}}$ while the final electricity usage is 4202 $\frac{\text{TWh}}{\text{a}}$. To balance this deficit gas imports are mandatory. Similar to scenario 1 the BEV has the highest electricity demand accounting for 2378 $\frac{\text{TWh}}{\text{a}}$. In this scenario, the gas-powered CHP plants have a supporting function for the entire future exergy system. Due to the increased amount of renewable energy production the batteries in the households as well as the pumped storage are utilized to store the excess electricity. The gas imports account for 8294 $\frac{\text{TWh}}{\text{a}}$ which represents a decrease of approx. 25 % compared to scenario 1 but still indicates an increase of 100 % compared to the status quo. The imported gas is primarily used as energy carrier for fuel cell cars which represent 41 %, the thermal utilization which represents 49 % of the entire gas imports and the gas-powered CHP plant is supplied with 580 $\frac{\text{TWh}}{\text{a}}$. The same trend development is observed in both scenarios, namely the transition towards cars that use electricity or fuel cells as energy carriers due to the high exergy ratios as describe in Chapter 4.5. The modeling results indicate that the heat pumps will increase their usage in 2050. Optimizing the system using excess heat and heat pumps, it is created an efficient and sustainable energy system. In this way, the exergy losses are reduced.

5 CONCLUSION & FUTURE OUTLOOK

This thesis set a goal to present how will the future exergy system look like. The supply side for 2050 is based on two different scenarios which indicated different evolution of the RES. scenario 1 took a constant development of the RES while scenario 2 had a progressive approach. Furthermore, four main sectors i.e., industry, transport, and households and services with their corresponding final exergy applications are analyzed. To gather information in this regard about the future exergy system, the optimization program oemof was used. The purpose of this simulation is to reduce the usage of the primary exergy.

As described in Chapter 4 both scenarios are strongly dependent on the gas import. From an exergetic point of view this phenomenon has a high impact on the overall efficiency of the system but if the energy security of the EU-27* is considered then this dependency is not optimal. In such cases, it is important to find a compromise between the efficiency of the system and the security of Europe. It is also important to mention that based on this simulation it is not possible to distinguish between the number of countries that export their gas to EU-27*. It is also important to mention that other energy carriers i.e., nuclear energy were not considered which resulted in this high amount of gas imports. Alone nuclear energy fulfills 69 % of the demand in France and makes up 50.8 % in Belgium. Consequently, the progression of nuclear power is a factor that may feasibly affect the share of energy production within the EU-27* by 2050. Therefore, it is an aspect that must be considered in further research [70].

Furthermore, both scenarios indicate that the future transport sector will be strongly dominated by two types of energy carriers. On one hand, is the electricity and on the other hand the gas, either as SNG or H_2. As described above these two types of energy carriers share the highest exergy ratio, 100 % and 95 % respectively. This work described the technologies applied in order to achieve the highest efficiency but did not consider the exergy losses or exergy destruction. On the one hand, by identifying and quantifying these losses, we can pinpoint inefficiencies in the system and make targeted improvements, ultimately enhancing the system's performance and sustainability. On the other hand, by quantifying exergy destruction, we can identify where in the process most of the inefficiencies occur. Therefore, in order to better represent the future exergy system these parameters could also be investigated.

Another interesting realization is the increased usage of heat pumps in the future exergy system. In both scenarios is distinguished between low and medium-temperature heat pumps. The heat pumps support the system by increasing its exergy efficiency based on their technology, namely the possibility of increasing the temperature of a system taking as a reference the i.e., ambient temperature. Based on the presence of two heating grids is possible to supply each other in an efficient way because the temperature difference between these two grids is lower than the temperature difference between the operating level and the environment. Therefore, the exergy destruction will be reduced.

Based on the EU-27* goals and the trend in a higher development of the RES scenario 2 presents one path which can conduce to reaching the targets. If scenario 2 is set as a target and all the parameters defined in this work are feasible then a primary exergy efficiency of 23 % can be achieved compared to the status quo. On the other hand, if scenario 1 is implemented the primary exergy efficiency reaches approx. 32 %. The results indicate that the process heat at 1000°C, the chemical industry and primary steel-making as well as the transport sector demand the highest amount of exergy. From the overall analyzed sectors, process heat at 1000°C stand for 32 %, the chemical and steel-making industries stand for 21 %, and the transport sector stands for 26 %.

Another aspect that influences the quality of the results is the data-gathering process. Unfortunately, no unified database regarding the transport sector, specifically FEC as well as data about the production and recycling of plastic was identified. Therefore, different assumptions are made which subsequently impacted the results of the simulation.

Overall, the future energy system of the EU implies a high electrification and gasification degree accompanied by challenges regarding the increased flexibility of the entire system, the capability and the performance of the future storage as well as the high reliance on gas imports.

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7 APPENDIX

Table 13: Weighting factors for different systems

Country	Weighted Wind Power	Weighted Hydropower	Weighted Solar Power	Weighted Heat Consumption
Austria	0.00278	0.07347	0.01602	0.027645
Belgium	0.00149	0.00082	0.01006	0.035838
Bulgaria	0.00171	0.01362	0.03204	0.007904
Croatia	0.00152	0.01482	0.00727	0.007604
Cyprus	0.00000	0.01519	0.00261	0.001031
Czech Republic	0.00696	0.00424	0.02608	0.030187
Denmark	0.02475	0.00016	0.01677	0.016765
Estonia	0.01280	0.00049	0.00540	0.003695
Finland	0.04467	0.02507	0.00950	0.027435
France	0.14366	0.10808	0.17418	0.147066
Germany	0.04316	0.03909	0.10693	0.215725
Greece	0.01789	0.01675	0.02329	0.012005
Hungary	0.00522	0.00464	0.03893	0.021961
Ireland	0.14233	0.00233	0.02310	0.010199
Italy	0.02849	0.08214	0.10283	0.123418
Latvia	0.02393	0.00617	0.00894	0.005238
Liechtenstein	0.00000	0.00000	0.00000	0.000000
Lithuania	0.02469	0.00174	0.01397	0.005238
Luxembourg	0.00009	0.00054	0.00056	0.002351
Norway	0.20803	0.26340	0.00000	0.018149
Poland	0.05292	0.00810	0.08495	0.069397
Portugal	0.01461	0.02664	0.01714	0.009479
Romania	0.00398	0.04354	0.08234	0.027178
Slovakia	0.00206	0.00905	0.01323	0.011507
Slovenia	0.00003	0.00964	0.00261	0.003864
Spain	0.10111	0.05035	0.13394	0.058500
Sweden	0.06045	0.12243	0.01956	0.030307
Switzerland	0.00000	0.05576	0.01155	0.020755
Netherlands	0.03067	0.00151	0.01621	0.049419

Process Demand (Without Conversions)
Hydrogen for Direct Reduction of Iron Ore in Crude Steel Production
Electricity for Electric Arc Furnance in Curde Steel Production
Electricity for Information and Communication Technology

Table 14: Useful exergy of different applications for Scenario 1 und 2

Applications	[TWh]
Demand Non-Energy Use	1385
Demand Iron and Steel Making (Coal)	0
Demand Iron and Steel Making (Electricity)	130
Demand Iron and Steel Making (Hydrogen)	51
Heat Demand 25°C	54
Heat Demand 80°C	141
Heat Demand 150°C	506
Heat Demand 350°C	229
Heat Demand 1000°C	2364
Transport Demand Car (long distance)	69
Transport Demand Car (short distance)	1396
Transport Demand Light Duty Truck (long-distance)	77
Transport Demand Light Duty Truck (short distance)	36
Transport Demand Heavy Duty Truck (long-distance)	43
Transport Demand Heavy Duty Truck (short distance)	129
Transport Demand Rail with Powerline	60
Transport Demand Rail without Powerline	4
Transport Demand Navigation	29
Transport Demand Aviation	51
Transport Demand Pipeline	51
Work Demand Stationary Engines	195
Lighting Demand	52
ICT-Demand	458
Electrochemical Demand	0

Table 15: Primary exergy supply in 2050 scenario 1

Technology	[TWh]
Photovoltaic Systems	677
Wind Power plants	1355
Woody Biomass production	1110
Hydropower plants	372
Sustainable Natural Gas production	740
Hydrogen Import	1000
Coal-Import	1000
Industrial Low-Temperature Excess Heat	5743
Electricity Import	0
SNG-Import	100
Woody Biomass Import	100
Ethanol fuel/Biodiesel Import	100
Ethanol fuel/Biodiesel production	0
Waste Accumulation	0
Solar Thermal Generation	0
Geothermal Generation	0

Table 16: Primary exergy supply in 2050 scenario 2

Technology	[TWh]
Photovoltaic Systems	1108
Wind Power plants	4006
Woody Biomass production	426
Hydropower plants	415
Sustainable Natural Gas production	284
Hydrogen Import	1000
Coal-Import	1000
Industrial Low-Temperature Excess Heat	5743
Electricity Import	0
SNG-Import	100
Woody Biomass Import	100
Ethanol fuel/Biodiesel Import	100
Ethanol fuel/Biodiesel production	0
Waste Accumulation	0
Solar Thermal Generation	0
Geothermal Generation	0

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