University of Southern Denmark
The Maersk Mc-Kinney Moller Institute

Cross-border utilization of renewable energy in Europe

Master Thesis - Energy Technology

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Abstract

Lowering impacts related to climate change have become a global challenge. With an increase in scarcity of resources and rising temperatures, the need for renewable and sustainable solutions has grown. Solving climate-related issues have not just been of national interest, but have reached international awareness. Alongside the expansion of renewable energy available in the electricity grid, the dependency on neighboring countries has increased. This thesis will examine possible designs for a sustainable European energy system. By gathering information related to resource availability of biomass and renewable energy services along with energy demand and interconnector restrictions, the thesis analyzes a European energy system. The analysis is carried out using a macro-level holistic approach using the Simulation of Flexible and Renewable Energy sources Tool, Sifre. For simplicity reasons, Europe is divided into five clusters: North, Central, West, South, and South East Europe. The thesis will create four simulation scenarios in the Sifre Tool. First is a reference scenario, serves as a baseline and comparison throughout the thesis. Alongside the base scenario, is the renewable scenario where restrictions on renewable energy capacities are removed. The thesis also investigates the consequences of increasing the allowed capacity on gas and electricity interconnection lines between clusters. Lastly, the possibility of trading hydrogen across Europe is analyzed.

Based on simulation results, it is found that allowing more renewable electricity in the system yielded a more flexible system with lower socio-economic costs. A more flexible system provides better conditions for fuel and hydrogen in hours with excess electricity production along with generally lower electricity prices. Also, when allowing for more renewable energy and higher interconnector capacity in the scenarios, the need for backup capacity lowered. The higher availability of electricity reasons the lower need for backup capacity. Generally, the thesis found the northern, western, and southeastern cluster to be the most resource secure cluster. Likewise, the central and southern clusters were more dependent on imported resources in order to meet energy demands.

Acknowledgements

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However, this thesis could not have reached this level of quality without the help of Abid Rabbani, Assistant Professor at SDU Life Cycle Engineering. Therefore, I would like to thank him for his comments, suggestions, and discussions throughout the investigations related to the project.

This thesis further is done in collaboration with the Danish Transmission System Operator, Energinet, in the department *System perspective*. Anders Bavnhøj Hansen, Chief Engineer, has served as a company supervisor on this project. I would also like to thank him for the great discussions while working on the thesis, along with being very helpful with data gathering. Lastly, I would like to thank Mette Gamst, Senior System Analyst, for the constructive guidance with the simulation tool applied in the project.

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Nomenclature

ADAPT	Adaptive Planing Tool
BEUR	Billion Euros
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
DAC	Direct Air Capture
DEA	The Danish Energy Agency
DH	District Heating
ENTSO – E/G	European Network of Transmission System Operators fro Electricity/Gas
HTPH	High-Temperature Process Heat
IEA	The International Energy Agency
LNG	Liquid Natural Gas
LTPH	Low-Temperature Process Heat
MEUR	Million Euros
PV	Photovoltaic
RWGS	Reverse Water Gas Shift
Sifre	Simulation of Flexible and Renewable Energy
SMR	Steam Methane Reforming
Syngas	Synthetic gas, mainly Hydrogen and Carbon monoxide
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
WGS	Water Gas Shift

1 Introduction

Intermittent power producers are widely known and implemented in the power system to lower emissions and meet political goals related to climate change[1]. However, as the share of renewable power producers increase, electricity production from current capacity decreases. With higher reliance on intermittent power producers, the need for a flexible energy system arises. A flexible energy system refers to a system, which can utilize excess electricity in hours with high electricity production from wind turbines and photovoltaic cells. Likewise, the need for backup capacity in hours with insufficient wind and solar resources available has become crucial.

In a flexible energy system, the availability to transfer energy resources across sectors have been found vital for meeting the security of supply. The method of sector coupling has, in recent years, become a solution to ensure a resilient, sustainable energy system[2]. Sector coupling allows flexible energy trade between the heating, electricity, gas, and transport sectors. Utilizing residual electricity for the production of gas and fuel to the transport sector is one way of having a more flexible system. Figure 1 shows an example of flexibility in an energy system. In hours with high production of electricity from wind turbines, electricity prices are generally low. In hours with low electricity prices, it is beneficial to produce hydrogen through an electrolysis unit. Furthermore, in hours with high electricity prices, storage extraction is more beneficial to meet hydrogen demands. Also, wind resources are more available in hours with low electricity prices. This dynamic is what is meant by the flexible production of gas and fuel throughout the thesis.

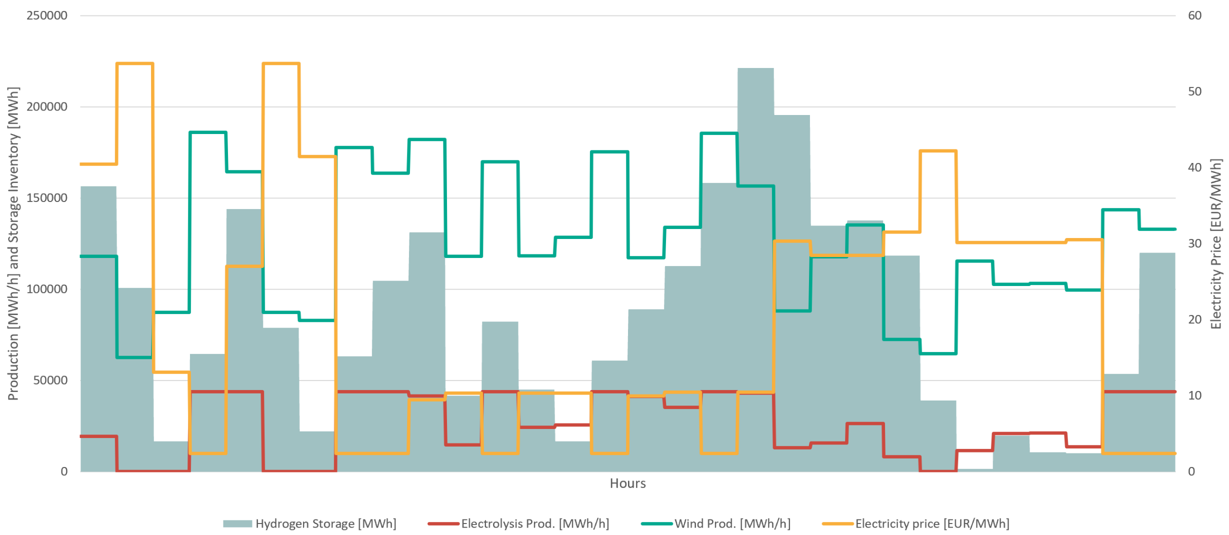

Figure 1: The figure shows the flexible production in an electrolysis unit, where the production increases with lower electricity prices and decreases in hours with high electricity prices. In hours with high electricity prices, the energy system depends on storage extraction to meet the hydrogen demand.

2 Problem Statement

Over the past decades, the concern for climate change has grown. The term global warming has become well-known throughout the world. A significant increase in average global temperature and more extreme weather phenomena have become more frequent. Figure 2 shows measurements performed by the National Aeronautics and Space Administration, NASA, on average global temperature[3]. The Figure shows the mean deviation of temperature on a global level with 1880 as the reference year. The Figure reveals a significant, almost consistent increase since the 1960s. The increase in temperature is directly related to the emission of greenhouse gases. Greenhouse gases is a term used to describe CO_2 and CO_2-equivalent gases (e.g., Methane and Nitrogen Oxide). Several studies have proved the relationship between the emission levels and the deviation in temperature. The higher the atmospheric concentrations of greenhouse gases, the higher the increase in temperature. It is also evident that smaller emission levels of greenhouse gases yield smaller increases in average temperature[4]. The greenhouse gasses absorb the heat from the solar radiation, which is reflected from the surface of the earth, preventing it from leaving the atmosphere. This phenomenon causes the temperature to increase. A deviation in temperature interferes with the globe's ecosystem resulting in extreme weather conditions including firestorms, typhoons, floods, and droughts[5].

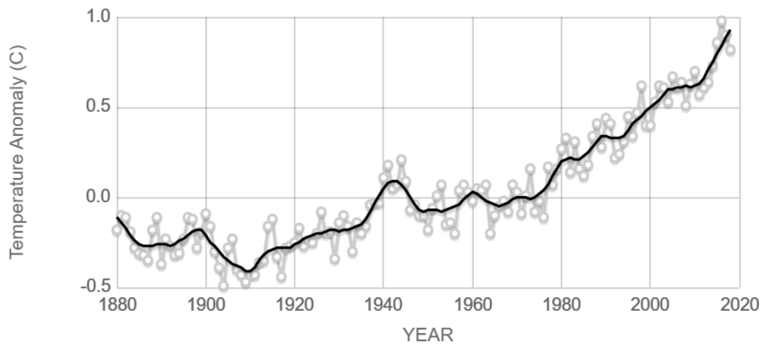

Figure 2: The figure reveals the Temperature Anomalies on Global Scale compared to 1880. The data is gathered by the National Aeronautics and Space Administration and shows a significant increase in temperature over the past decades[3].

The increase in temperature, along with the scarcity of conventional fuels, create incentives for the implementation of sustainable and climate-resilient solutions[5]. Politicians and civilians support this throughout the world. Several international agreements have been decided to lower emissions of greenhouse gases. Among these are the Paris agreement, which is an international treaty signed under the United Nations Framework Convention on Climate Change in December 2015. The treaty entered into force on November 4^{th} 2016, and has been signed by 197 countries and ratified by 187 as of the compilation of this thesis, June 2020. The objective of the treaty is to conduct a binding and universal agreement to limit the emissions of greenhouse gases and ensure the average global temperature would not exceed 2 degrees Celsius compared to pre-industrial levels, 1760[1].

The environmental impact must be reduced to minimize the consequences of climate change. A tool used for evaluating the trends in the environmental impact and locate the off-spring is the IPAT-equation. The IPAT-equation is a mathematical representation of the factors which have an impact on the climate. The general concept of the IPAT-equation is to divide the environmental impact into three main factors. The three factors are Population, Affluence, and Technology.

$$\textbf{Impact} = \textbf{Population}\ [\text{No. of persons}] \times \textbf{Affluence}\ \left[\frac{\text{Consumption}}{\text{Person}}\right] \times \textbf{Technology}\ \left[\frac{\text{Emission}}{\text{Consumption}}\right]$$

The first parameter is the population. As the world population increases, the environmental impact increases similarly. The population has increased from 1 billion in 1800 to 7.6 billion in 2017[6]. However, the growth has slowed down, and UN experts expect the growth will slow further down over the next decades. The experts predict the population will be between 10 and 12 billion in 2100. However, it will not increase further by the end of this century. The experts mainly believe this prediction as the number of born children has decreased from 5 children pr. woman in 1965 to 2.5 children pr. woman in 2017[6].

The second parameter is Affluence, also known as economic growth. As more people experience wealth, the environmental impact increases. Generally, more people have surpassed extreme poverty into higher income levels making people spend more. From 1800 to 2017, the share of the world population living in extreme poverty has decreased from 85% to 9%[7].

The third parameter, and most relevant for this thesis, is the technology. With the population increasing and becoming more affluent, the technology must compensate for the impact to lower. The impact of technology is accounted for per goods purchased. Through the development of sustainable technology, the environmental impact can be lowered[8]. This thesis will aim to implement sustainable technologies to provide renewable energy supply to electricity, heat, and transport without conflicting with current growth tendencies or demands.

In today's Denmark, 50% of the electricity is covered by renewable energy from wind power and photovoltaic cells[9]. However, if all energy sectors are considered, the renewable energy share is below one-third of the supply. The tendency is the same in the rest of Europe[10]. One way to reach the goal of a 100% sustainable energy system is to utilize renewable electricity production across all energy sectors. Sector coupling is one way, where surplus renewable electricity is converted to hydrogen and syngas to make electrofuels. This thesis will investigate sector coupling on a European level to identify and resolve issues that arise while integrating the sectors mentioned previously and utilizing the production of renewable energy across borders. The analysis conducted in the thesis will represent a 2050 climate-neutral Europe, where the emissions of the net energy sector are kept at zero.

2.1 Outline

The thesis seeks to identify bottlenecks and to integrate complexities of a European renewable energy system; thereby, the detail-level is confined to a macro-level holistic approach, and intricate details are kept at a minimum. The model includes all ENTSO-E/G countries, which will be divided into five geographical areas. A model is built with information to locate the resources and scarcities of each sector. The goal is to find solutions to lowering energy shortage and ensure optimal use of resources. The product of the thesis will be a model, which can detect the capabilities, potential, and restrictions of the European energy system. The aim is to localize system complexities in a climate-neutral energy system and develop scenarios to solve them.

Tasks in the thesis:

- Data gathering concerning energy demands across Europe along with constraints on biomass resources, capacity factors on renewable energy, and interconnection capacity between clusters. Energinet will provide the data along with being obtained through energy agencies, ENTSO-E/G, and other European transmission system operators.
- An initial model based on data obtained is made in the energy simulation tool Sifre (Simulation of Flexible and Renewable Energy) developed by Energinet to provide initial results.
- Based on the model made, an analysis is conducted to locate the challenges in the European renewable energy system. Challenges would include a lack of resources, insufficient infrastructure, and unutilized resources.
- Based on initial analysis, several scenarios for solving challenges will be conducted. The simulation scenarios will be carried out in Sifre and evaluated from a technical and socio-economic perspective.

2.2 Scope and Delimitation

Before this thesis, several studies have been conducted, investigating sustainable energy systems on a national and international level. The International Energy Agency, IEA, has developed a system perspective on a global level[11]. ENTSO-E/G has made European strategies for electricity and gas sector[12]. Energinet has made several system perspectives investigating Danish Energy systems[2]. The studies present scenarios for solving the challenges related to climate change. The thesis will work as an extent from these studies and locate resources and trading possibilities across ENTSO-E/G member countries.

Figure 3: The figure shows the map of European clusters. For simplicity reasons, the ENTSO-E/G countries are divided into five clusters. This map shows the division. Due to its geographical location, Iceland is not included in this thesis.

This study is done in collaboration with the Danish transmission system operator, TSO, Energinet. Energinet is part of the European Network of Transmission System Operator for Electricity/Gas, ENTSO-E/G. ENTSO-E/G consists of a total of 43 TSOs in 36 countries across Europe. The establishment of ENTSO-E/G occurred in 2009 by the European Union's Third Legislative Package, which aims to work towards a more liberalized gas and electricity market. However, the agenda for ENTSO-E/G also includes maintaining the security of supply with the increasing amount of renewable energy suppliers in the electricity grid. According to ENTSO-E/G, this is done through several critical factors, which include innovation, a market-based approach, customer focus, stakeholder focus, security of supply, flexibility, and regional cooperation[13].

This thesis will provide the technical and economic overview of possibilities for a sustainable Europe. For simplicity reasons, the European countries are divided into five clusters in this thesis. The constraints and resource potentials are found within the different clusters and are presented on a cluster level. Figure 3 shows the deviation of countries into clusters. The thesis will though energy system modeling, simulate a yearly production of electricity, heat, gas, and fuels in Europe in the year 2050. The thesis will use current available sustainable solutions and processes, along with currently available data and costs of technologies. Due to its geographical location, the thesis will not include the country Iceland in the model.

3 Methodology

This section provides a description of the methodology applied throughout the thesis and elaborates on the methods applied to solve the challenges described in the problem statement. The thesis sets out to investigate a sustainable European energy system through energy system modeling and analysis. The simulation year is 2050, where a 100% renewable energy system is expected to be a reality[1]. This section will expand on the terms energy system analysis and sustainability, along with present relevant references applied in the thesis. The section sets the boundaries for the study and is extended and applied throughout the thesis.

The thesis is conducted with a holistic approach, meaning the emphasis is on the big perspective on the energy system and covering the demand within the electricity, heat, and transport sector[14]. The European demand and available resources are found within the five clusters presented in Section 2.2. The analysis is done in an energy system analysis tool, where a simplified model of an energy system is built. Simplifying the European energy system into five clusters yields a less complex system than reality. However, the system is considered realistic as an initial investigation of overall energy flows and available resources throughout Europe. The interconnection capacities within the clusters are neglected, and the bottlenecks within clusters are not considered in this thesis.

The thesis does not include coal, natural gas, nor nuclear energy due to the emission levels, residual waste, and resource scarcity related to these[15]. Coal, natural gas, and nuclear resources are categorized as stock resources. Stock resources are regenerated so slowly that they practically exist in a finite and fixed quantity. Therefore regeneration of stock resources is commonly neglected. The thesis includes fund and flow resources. Fund resources are consumed at a paste, which does not result in depletion and ensures sustainable regeneration[16][17]. The fund resources considered in the thesis are biomass resources. The biomass resources can generally be divided into dry and wet biomass. Dry biomass is wood resources, and these are more expensive to gasify than wet biomass(Appendix A.18)[2]. The wet biomass resources in the thesis are divided into manure, straw, organic waste, and sludge. The wet biomass resources are gasified through the anaerobic digestion process[18].

After the initial study, several suggestions for insurance of equity use of resources are conducted. These include expanding electric and gas interconnections and including interconnectors for hydrogen. The maximum capacities for renewable power production units are also increased in one scenario to investigate the consequences of changes in the system. The thesis focuses on the investigation of the utilization of cross-border renewable energy in Europe. Therefore the changes described are used to investigate the effect of adjustments on the system. These are used to conclude on overall implications on technical and socio-economic performance.

3.1 Data and Sources

For the initial analysis, the energy system is modeled with the resource availability found through two main studies. First, is the Alterra study *Atlas of EU biomass potential*[16], where a detailed analysis of available biomass resources across Europe are presented. The study considers a variety of biomass sources, which is simplified into five categories in this thesis, wood, straw, manure, sludge, and organic waste. The Alterra study consists of two scenarios, a reference scenario, and a sustainability scenario. This thesis seeks to develop an energy system, which does not compete with food stocks and consumes biomass at a pace where it is sustainable. Hence, the sustainable scenario is selected for the investigation of available biomass resources throughout Europe. The second study applied is the ten-year network development plan 2020, TYNDP20[12]. TYNDP20 is conducted by ENTSO-E/G and consists of potentials for renewable power-producing capacity in 2040 for each ENTSO-E/G member respectively. The renewable power producing units considered in this thesis are onshore and offshore wind turbines, photovoltaic cells, and hydropower plants. Further combined heat and power plants, CHPs, are modeled, and their capacities optimized. These are fueled by biomass resources or synthetic gases e.g., methane, hydrogen, and biogas.

Other essential references applied in the thesis include data from the international energy agency, IEA, and more references available through ENTSO-E/G. Energy demands across sectors investigated in the system are provided by IEA[11]. Interconnector capacities on electricity and gas are provided mostly by ENTSO-E/G[19]. However, in some cases, data is collected from relevant transmission system operators as well[20][21][22].

4 Energy Demand and Resource Constraints

This section serves the purpose of examining the demand and available resources in the five clusters previously presented. This section contains a presentation of the data used as the backbone of the simulation in Sifre. The section can give the first indication of constraints within a sustainable European energy system. The thesis will include sector coupling as part of the solution for covering the energy demands sustainably. To model an energy system with sectors coupling the energy demand is found within both the electricity, transport and heating sector, these sectors are further divided into different types of demands.

As stated in Section 3, this thesis aims to construct a 100% sustainable European energy system. This entails the sustainable use of bio-energy resources and no use of nuclear energy. This Section will unfold the availability of bioenergy and renewable power production units across Europe.

4.1 Energy Demands According to Sectors Across Europe

The energy demands are divided into three sectors: electricity, heating, and transportation demand. Each of these sectors can be further divided into different types of demands. Section 4.1.1 to 4.1.3 contains estimations of demands for the five clusters within the three sectors respectively. The estimations are based on data from the International Energy Agency, IEA[11], and the Ten Year Network Development Plan 2020, TYNDP20[12]. In the case of the data from IEA, 2017, data have been adjusted to provide a qualified estimation of energy demands in 2050. The European Commission provides the factors for development in demand. The data from IEA helps estimate demands within the heating and transport sectors. The heat demand is expected to remain more or less the same, as the efficiency in households and the industrial process is expected to improve, while the population grows. Concerning the transport demand, the mechanical demand is found through the consumption data of fuels from the IEA dataset[11]. Articles from the European Commission and the International Energy Agency are applied to create a forecast for the transport sector. The demand within the transport sector is expected to increase within aviation, road, and train transportation means, while the demand is expected to decrease for sea transportation means[23][24][25]. In the electricity sector, data from TYNDP20 is applied, where data from 2040 is used[12].

4.1.1 Electricity Demand

The electricity demand is not distinguished between commercial and industrial needs and is instead looked upon as one demand within the five clusters, respectively. Energy demands are given on the country level in the datasets provided by ENTSO-E/G and are summed for the five clusters[12]. The number given in the data set is a yearly demand. The distribution profile applied in the energy system simulation is the distribution profile for electricity consumption in western Denmark. Using a Danish distribution profile is not exact, and peaks of electricity consumption may differ throughout Europe. However, the profiles are simplified due to low data availability. The base scenario does not implement any flexibility of the use of electricity for the five clusters.

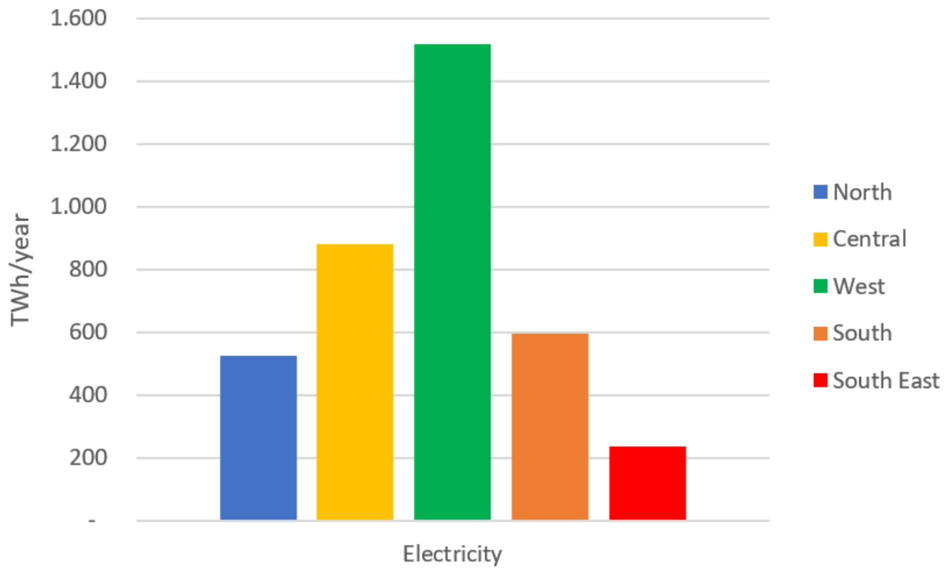

Figure 4: The figure shows the electricity demand across Europe. Based on data from the ENTSO-E/G[12], the electricity demand in each of the five clusters is found. Appendix B.1 contains a table showing the exact values used as input in Sifre.

Figure 4 shows the electricity demand within the five clusters given in TWh a year. Looking at the figure, it is evident that coherence between population size in a cluster and its electricity demand is present. The more population-dense clusters have a higher demand for electricity. This is evident by looking at the western cluster, which is the most population-dense cluster and also has the highest electricity demand. The central cluster has high demand, apparently due to its population size. Looking at the figure, it is clear that the southeastern cluster has the lowest electricity demand. The southeastern cluster also has the lowest population size. The northern and southern clusters have an electricity demand between the central and southeastern, probably due to the medium population size.

4.1.2 Heat Demand

The heating sector considers three types of demands: District Heating, Low-Temperature Process Heat, and High-Temperature Process Heat, where the industrial processes mainly consume the last two. Residential and commercial heating demands consume district heating. The consumption profiles applied for the heating demand is forwarded from Energinet. Therefore the District heating profile applied is the Danish consumption pattern for heating. LTPH and HTPH have the same profiles for industrial consumption patterns. The model does not allow heating demands to be non-flexible. However, the Sifre model includes storage units to balance heating demand.

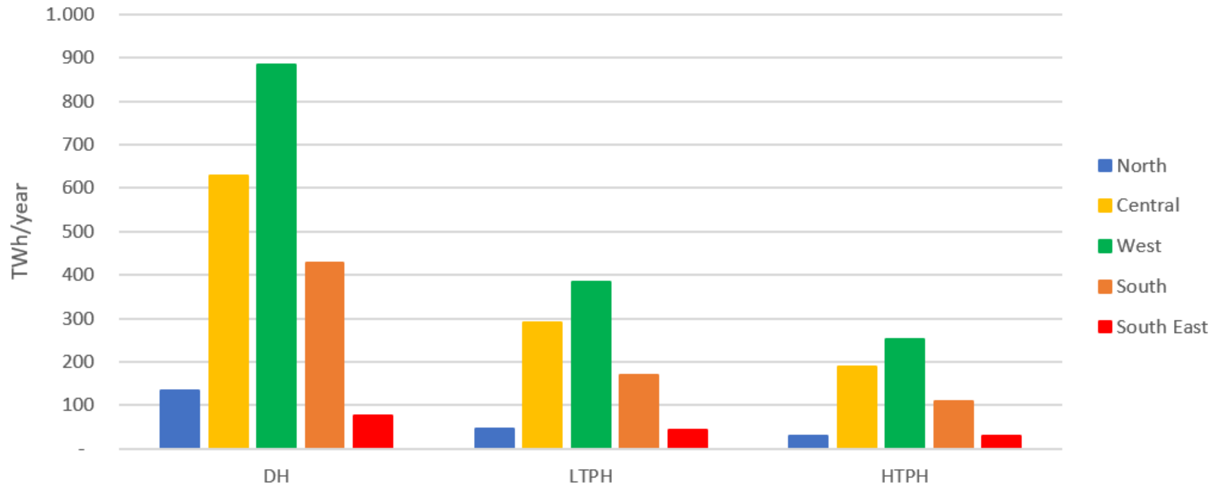

Figure 5: The figure shows the heat demand across Europe. Based on data from the International Energy Agency[11], the District Heating, Low-Temperature Process Heat, and High-Temperature Process heat demands in each of the five clusters are found. Appendix B.2 contains a table showing the exact values used as input in Sifre.

Figure 5 shows the size of the demands divided into the five clusters. Same as for the electricity demand, the district heating demand is substantial in coherence with the population in the clusters. The western, southern, and central clusters are the most population-dense and therefore have more extensive space and domestic heating demand. The north and southeast clusters have lower population density, and therefore the district heating demand is lower. The LTPH and HTPH demands are generally lower than the DH demands in all five clusters. The demands do follow the same distribution as the distribution for DH with few alterations. The process heating for the northern cluster is on the same level as the southeastern cluster, making it evident that the industry demand in North Europe is limited compared to the other clusters.

4.1.3 Transport Demand

The transport sector is divided into four types of demands: Aviation, road, sea, and rail. The IEA data yielded the quantity of fuels (coal, oil, natural gas, biofuels, and electricity) consumed in each of the countries[11]. Based on estimations from Energinet along with combustion efficiencies, the consumption of these fuels was distributed into the four types of demands. The demands all have a constant consumption profile and great storage to balance the production fuels cost-efficiently.

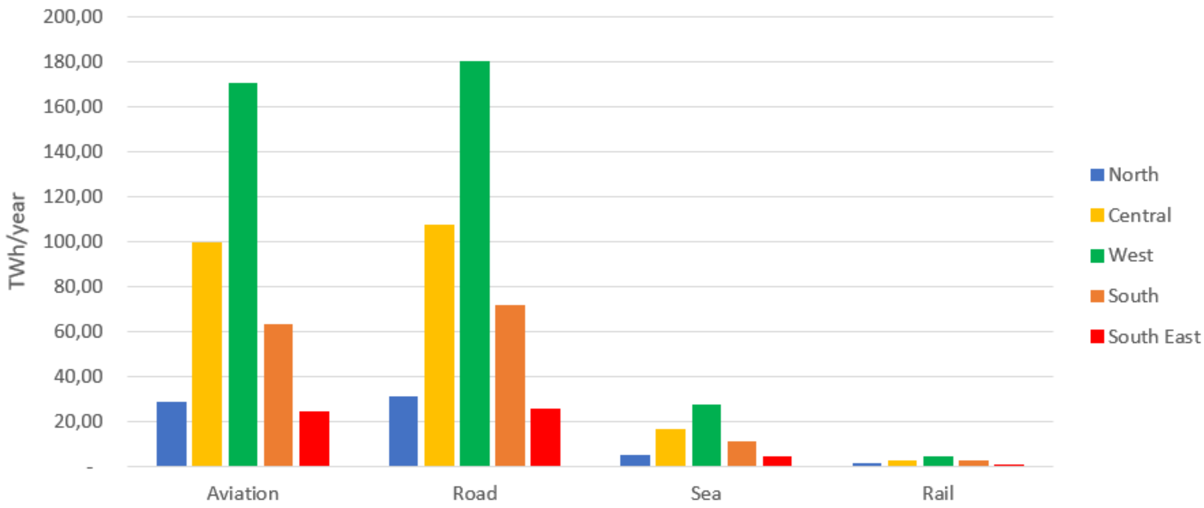

Figure 6: The figure shows the transport demand across Europe. Based on data from the International Energy Agency[11], the transport demand within the Aviation, Road, Sea, and Rail sector in each of the five clusters is found. Appendix B.3 contains a table showing the exact values used as input in Sifre.

Looking at Figure 6, the four types of transport demands are shown across the five clusters. Aviation and road demands are significantly higher than the sea and rail demands. The distribution between the clusters is following the same pattern as for the heating and electricity sector. The western, central, and southern clusters have the highest transport demand. The main reason is assumed to be the size of the population in the clusters. The northern and southeastern clusters are close in demand on all four types of demands and significantly lower than the other clusters.

4.2 Resource Constraints in a Sustainable European Energy System

This section serves the purpose of presenting the data input to Sifre concerning the availability of biomass and renewable resource. In Section 3, the scope of the thesis was restricted not to include nuclear energy. For the investigation of the availability of resources across Europe, two primary studies are applied.

First, the availability of biomass resources across Europe is found using the Alterra study

Atlas of EU biomass potential[16]. Alterra conducted the study in 2012, intending to provide information regarding the availability of different biomass feedstocks and their cost. The study serves as the fundamental basis for further discussion and guidance for energy simulation. The study is funded by and conducted for the European Union's Intelligent Energy Program. The selection of the Alterra study is done due to its detail level and extent for locating and price-setting resources in Europe. The Alterra study only includes countries, which are members of the European Parliament, hence not all ENTSO-E/G member countries are included. Appendix B.4 contains a map showing the countries included in the Alterra study. The data available in the Alterra study is especially limited in the Southeastern cluster. However, more data is available in more population-dense countries, the study is therefore selected, despite its deficiencies. The Alterra study divides the biomass resources into 31 types. For simplification reasons, this is limited to five types: Wood, sludge, organic waste, manure, and straw. This thesis will not include eatable biomass resources, e.g., maize, as there is a requirement not to compete with food. The simplification of biomass resources is done to simplify the Sifre model. The simplifications are shown in a table in Appendix B.5.

Secondly, the availability of renewable energy resources is found. In this thesis, renewable energy resources include onshore wind, offshore wind, solar, and hydro energy resources. The wind and solar energy resources are built in the model for each country individually and supply electricity to the electricity area in their clusters, respectively. The European Commission provides the profiles containing the capacity factors for wind and solar production units[26], and the distribution of production applied in the model is from the year 2017. Hydro plants are not a build-in application in the Sifre-software. Therefore the modeling of hydropower is done manually. The availability of hydro resources is simplified to one hydro plant for each cluster. Appendix B.6 shows the build-up of the hydro plant production unit in Sifre. The maximum availability of wind, solar, and hydro resources have been provided by the Ten Year Network Development Plan 2020, TYNDP20, conducted by the ENTSO-E/G[12]. The TYNDP20 study includes all ENTSO-E/G member countries, and the exact values for the potential can be found in Appendix B.7.

4.2.1 Biomass potential - Wood

Woody biomass is in this thesis modeled as wood chips and applied in the process of thermal gasification and burned in boilers/CHP plants. The Alterra study includes eleven different woody sources. The sources include residual wood from industries and sawmills, along with the more expensive round wood resources[16].

Figure 7 shows the biomass potential of the five clusters (x-axis) and their respective prices (y-axis). When looking at the figure, it is evident that the most substantial woody biomass resources are located in the northern, central, and western clusters. The southeastern cluster has the least woody biomass resources. However, the quantity of cheap resources is the same for the northern, southern, and southeastern clusters. The more costly woody biomass resources, e.g., round wood, are less available in the southern and southeastern clusters. The central and western clusters have higher quantities of less expensive woody biomass resources compared to the other clusters. The western cluster has the highest quantity. However, it is significantly more expensive than the resources located in the western and northern clusters.

The main point of interest for the woody biomass is that the significant resources are located in the western, northern, and central clusters. The central and northern clusters are most attractive due to the prices of the resources. It is essential to notice that Norway is not included in the Alterra Study, and the availability of woody biomass resources are expected to be even more significant in the northern cluster.

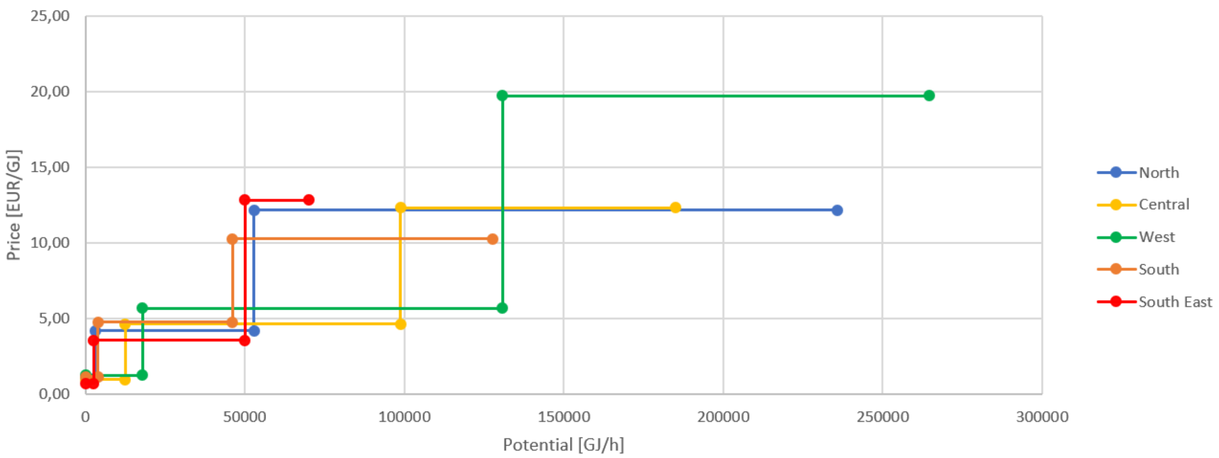

Figure 7: The figure shows wood resources across Europe. Quantity and price of available wood resources are divided into the five clusters. The graph is conducted based on the Dutch study by Alterra. In the study the availability of biomass resources across Europe are investigated[16]. Appendix B.4 contains a map showing the countries included in the study.

4.2.2 Biomass potential - Straw

Straw is in this thesis applied in the process for anaerobic digestion, where the product is biogas. Biogas is converted to methane, which is applied in the gas processes or for fuel production through steam methane reforming. The Alterra study includes four categories of straw biomass resources. The resources include both verge grass and the more expensive grass and straw resources.

Looking at Figure 8, it is apparent the larges straw biomass resources are in the western

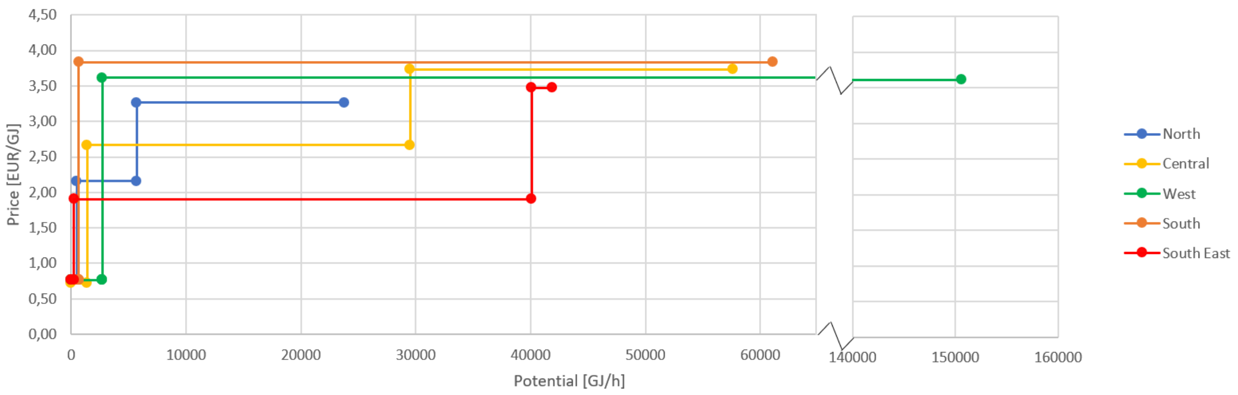

Figure 8: The figure shows straw resources across Europe. Quantity and price of available straw resources are divided from a country level into the five clusters. The graph is conducted based on the Dutch study by Alterra, where the availability of biomass resources across Europe are investigated[16]. Appendix B.4 contains a map showing the countries included in the study.

cluster, where the quantity is twice as large as the southern biomass resources. However, the prices of western resources are generally high. The availability of cheaper resources is in the southeastern and western clusters. The northern cluster also has less expensive straw biomass resources compared to the western cluster. However, the availability is low. The southern cluster has the second-highest availability of straw, but it is also the most expensive resource.

Generally, the take-away is that the most significant clusters for straw biomass resources are located in the southeastern and central clusters. The Alterra study has not included all countries in the southeastern cluster, meaning the quantity of straw resources is expected to be even more substantial.

4.2.3 Biomass potential - Sludge

Sludge is in this thesis defined as a group of waste products from industrial processes and wastewater treatment plants. The waste products are in this thesis applied in the anaerobic digestion process and can be used as an alternative to the slurry, though with a lower efficiency[27]. The Alterra study has two categories of sludge resources, the cheap black liquor and common sludge, which is slightly more expensive though still very lucrative.

Looking at Figure 9, it is evident that the most substantial sludge resources are in the northern cluster. Especially the cheap resource, black liquor is significant in the northern cluster, mainly due to the large paper industries in Finland and Sweden [16]. The western cluster has the second-largest resource pool of sludge. However, the western resource pool consists of a more significant share of the slightly costlier resources. The central cluster has a more significant share

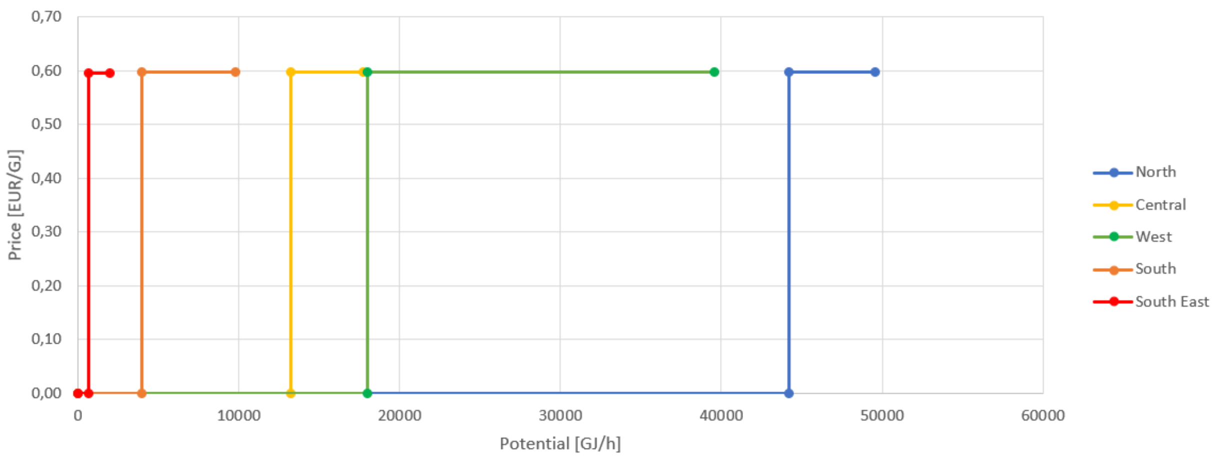

Figure 9: The figure shows sludge resources across Europe. Quantity and price of available sludge resources are divided into the five clusters. The graph is conducted based on the Dutch study by Alterra, where the availability of biomass resources across Europe are investigated [16]. Appendix B.4 contains a map showing the countries included in the study.

of the cheap sludge and a limited share of the slightly more expensive resources. The southern and southeastern clusters have a small share of sludge.

The price of sludge resources is uniform throughout the five clusters. The deviation between the five clusters is only related to the resource pool size. The southeastern cluster has the lowest availability of sludge, while the northern cluster has a large resource pool of sludge.

4.2.4 Biomass potential - Manure and Organic Waste

Manure and organic waste are input fuels in the anaerobic digestion process. Organic waste can also be used for waste incineration to produce heat and electricity. However, this option is not included in this thesis due to the availability of organic waste being low. The Alterra study does not have any subcategories for manure. Organic waste includes animal waste and municipal solid waste in the Alterra study.

Looking at Figure 10, the prices for manure and solid waste are generally constant in the five clusters. The availability of manure is highest in the western and central clusters. The prices in these two clusters are also competitive with the other clusters. The availability of manure is lowest, and the price higher in the northern and southeastern clusters. Manure is most cost-efficient in the southern cluster, with decent availability.

Organic waste is generally the same price across Europe, according to the Alterra Study. The price is a little below 3 EUR/GJ. However, organic waste is cheaper in the northern cluster. The availability of organic waste is low in the northern, southern, and southeastern clusters. The

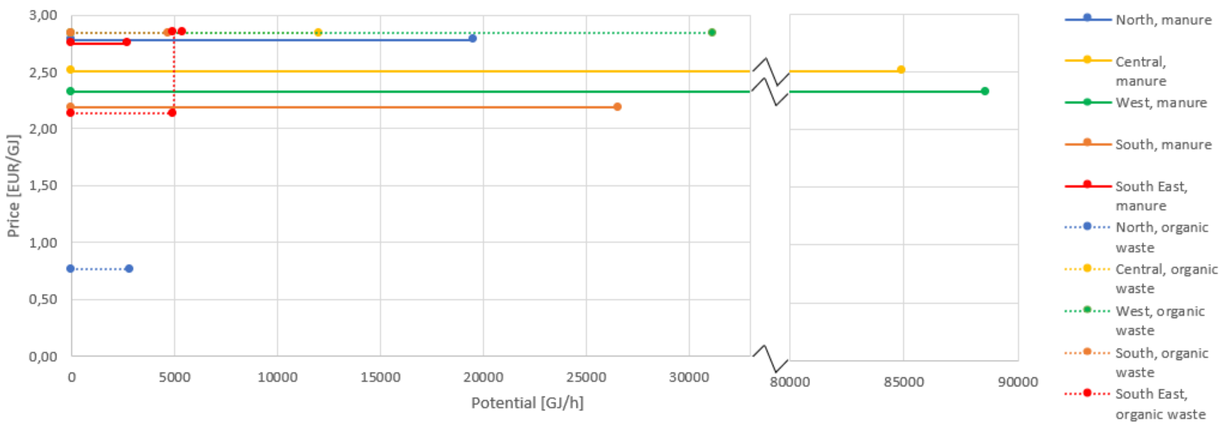

Figure 10: The figure shows manure and organic waste resources across Europe. Quantity and price of available manure and organic waste resources are divided into the five clusters. The graph is conducted based on the Dutch study by Alterra, which investigates the availability of biomass resources across Europe[16]. Appendix B.4 contains a map showing the countries included in the study.

availability of organic waste is higher in the central and western clusters.

The most significant potential for manure resources is in the western and central cluster. The takeaway regarding the organic waste potential is the most cost-efficient resources are in the northern cluster. However, the most substantial quantity is in the western cluster.

4.2.5 Availability of Renewable Energy Sources for Power Production

By using the TYNDP20 report, the potential of wind, hydro, and solar energy is found. Figure 11 contains four heat maps showing the availability of renewable resources on the country level. The maps present the resource availability of the five clusters. The potential is shown pr. Inhabitant. Figure 3 in Section 2.2 shows the deviation of the clusters.

North Europe North Europe includes the countries: Denmark, Norway, Sweden, Estonia, Latvia, and Lithuania. Looking at the green map containing information regarding the availability of onshore wind energy, it is evident the availability is generally high in the northern cluster. Looking at the purple map, it is clear that Denmark is the only country in the northern cluster, where the data for offshore wind energy resources are available. The Danish availability of offshore wind energy is the highest on the map, generally due to the availability in the North Sea [12]. The availability of solar energy resources (Orange map) is generally low in the northern cluster. The blue map shows that the availability of hydro energy is high in northern generally due to reservoirs in Norway, but Sweden, too, has high availability.

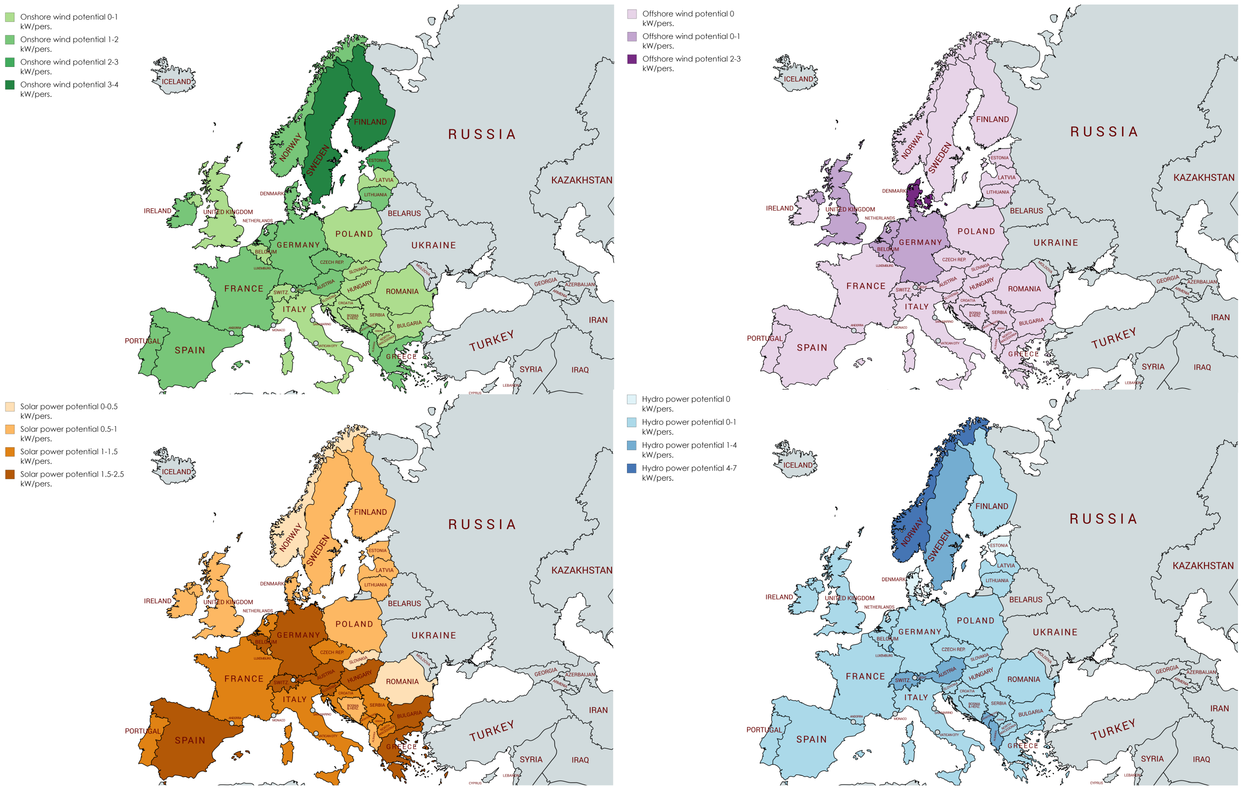

Figure 11: The figure shows the renewable energy availability across Europe. Based on the Ten Year Network Development Plan [12] conducted by ENTSO-E/G, a mapping is done on the potential of renewable energy sources across Europe. Appendix B.7 contains the exact values used as input in the Sifre simulation.

Central Europe The Central cluster consists of the following countries: Germany, Czech Republic, Poland, and the Slovak Republic. The green map reveals the central cluster has decent onshore wind availability in Germany and the Czech Republic and minor availability in Poland and the Slovak Republic too. Offshore wind resources are only considered in Germany in the central cluster. However, the purple map shows smaller availability of offshore energy, mainly due to the limited cost line of Germany. The orange map shows a high availability of solar energy in the central cluster, mainly in Germany, but also in the Czech Republic and Poland. The availability of hydro energy is generally limited in the central cluster.

West Europe The western cluster consists of eight countries: Belgium, France, Ireland, Luxembourg, Netherlands, Portugal, Spain, and the United Kingdom. The green map reveals a general decent amount of onshore wind energy resources in the western cluster. The UK, Belgium, and the Netherlands are considered for the offshore wind resource and generally have a fair amount of offshore wind resources available. The orange map shows a high availability of solar energy in the western cluster, mainly in Belgium and Spain. The blue map reveals a small availability of hydro energy throughout the western cluster, where only Luxembourg shows higher availability of hydro energy resources.

South Europe South Europe includes Austria, Croatia, Hungary, Italy, Slovenia, and Switzerland. The availability of onshore wind energy resources is generally low in the southern cluster. However, Austria shows to have higher onshore wind potential. Offshore wind is not present in the southern cluster. Solar energy resources are high in the southern cluster, especially in Switzerland, Austria, Slovenia, and Hungary. Hydro energy is highest in Switzerland and Austria, but present in all countries in the southern cluster.

South East Europe The southeastern cluster consists of the following countries: Albania, Bosnia Herzegovina, Bulgaria, Cyprus, Greece, Montenegro, Republic of North Macedonia, Romania, and Serbia. Looking at the green map, it is evident that the availability of onshore wind energy resources is low in the southeastern cluster. However, Montenegro, Greece, and Albania have higher potentials. The TYNDP20 report does not consider offshore wind energy in the southeastern cluster. The availability of solar power deviates across the southeastern cluster. However, apparent from the orange map, solar power shows exceptionally high availability in Greece and Bulgaria. Hydro energy is low in the southeastern cluster. However, Albania and Montenegro have higher potentials of hydropower.

4.3 Remarks on Energy System Boundaries

Based on the findings of the previous sections, this section will evaluate and discuss the ratio between resources available in the cluster and the demand within the cluster. Table 1 can used be to provide an overview of the main finding of the Section 4.2.

Looking at Table 1 the heat map indicates high demands in the central and western clusters while lower demands in the northern and southeastern clusters. The southern cluster is has a medium demand. The biomass and renewable energy resources rows are divided into different types of resources, following the figures previously presented.

Looking at the biomass resources, it is evident that the most abundant resource pool is available in the western cluster. The high availability in West Europe is fortunate as the cluster is also one with high demand. The northern cluster has a vast wood resource pool, which might leave a surplus for the production of syngas to the transport sector. The central cluster has a high demand. The resources in the central cluster are generally of medium size, with an exceptionally high resource pool of wood. Due to the high demand in the central cluster, methane or electricity might be imported from the neighboring clusters. The southern and southeastern clusters generally show low availability of biomass resources. Mainly South East Europe has low biomass availability; however, this cluster is also the one with the lowest demand. Also, not all countries from South East Europe are included in the Alterra Study, from which this investigation is based.

Table 1: The table contains a heat map used for comparison of demand and resources in the five clusters[16][11]. The darker the color the higher the demand or resource capacity.

Cluster	Demand	Biomass resources	Renewable Energy resources
North	Low	Wood	Onshore wind
		Straw	Offshore wind
		Manure/sludge	Solar
		Organic waste	Hydro
Central	High	Wood	Onshore wind
		Straw	Offshore wind
		Manure/sludge	Solar
		Organic waste	Hydro
West	High	Wood	Onshore wind
		Straw	Offshore wind
		Manure/sludge	Solar
		Organic waste	Hydro
South	Medium	Wood	Onshore wind
		Straw	Offshore wind
		Manure/sludge	Solar
		Organic waste	Hydro
South-East	Low	Wood	Onshore wind
		Straw	Offshore wind
		Manure/sludge	Solar
		Organic waste	Hydro

When considering the renewable energy resources, it can be reckoned the western cluster has a high resource share. The western cluster also has a high demand. The central cluster shows low renewable energy resource availability compared to its size of demand, especially within hydropower production. The northern cluster shows a high availability of renewable energy resources in contrast to its size of energy demand. The northern cluster has an exceptionally high availability of hydro production and also a significant capacity of wind energy. The southern cluster has low availability of wind energy, however a high share of solar and hydro energy. The southeastern cluster show low availability with all four renewable energy resources, despite the low demand in this cluster, the availability of renewable energy resources might be critical.

When comparing the demand and resource availability throughout the five clusters, it can generally be concluded that the western and northern cluster has the best opportunities for electricity and fuel production. The central cluster shows a generally medium availability. However, the central cluster also has a high demand, which could result in resource scarcity. The southern and southeastern clusters reveal lower resource availability. The southeastern cluster has a low demand, and therefore the resources available might be sufficient. However, the southern cluster has a higher demand. Combining the high demand with lower resource availability could result in the cluster being dependent on imported resources.

5 Modelling of 100% Renewable Energy System

The analysis of a sustainable European energy system is executed in the simulation tool Sifre (Simulation of Flexible and Renewable Energy sources). The simulation tool is developed and provided by the Danish Transmission System Operator, Energinet[2]. This Section will explain the primary functions and the build-up of the Sifre tool, along with the add-on optimization option applied in the thesis.

The Section will further present the energy pathways modeled to meet the demands with the resources available. The section will present the pathways briefly, as the goal is not to provide a detailed description of the production units included in the thesis, but rather show a holistic connection between production units and their interactions. For a more detailed description of the production units applied in the simulation tool, see Appendix A.

5.1 Introduction to Sifre and ADAPT

For the simulation of the sustainable European energy system, the thesis applies the simulation tool Sifre. The Sifre tool allows investigation of the European energy system on a cluster-level with the gas and electrical connections between these. The energy pathways within each cluster are further elaborated in Section 5.2. The ADAPT layer is an add-on in the Sifre model for the optimization of capacities on storages, production units, heat pumps, interconnection lines, and renewable technologies.

Sifre is a simulation tool used for market analysis. The intend of Sifre was initially to simulate Danish electrical and heating markets, mainly for modeling the production of CHP units in the Danish energy market. However, the simulation is not limited to any geographical location nor any energy type[28]. The software has, in recent years, allowed modeling of renewable fuel and gas production. All fuel inputs are looked upon as energy flows rather than considering the weight and calorific value of fuels.

Figure 12 shows the analogies of Sifre. The build-up of the Sifre model revolves around four types of units. The area, which is represented by the circle, is used to define the energy type. The area can have several functions; it can be a fuel input, e.g., wood chips or straw. It can also be an intermediate, e.g., syngas or a consumption node for heat or electricity. For fuel inputs, the availability of these can be determined to ensure sustainable consumption, e.g., biomass resources. Sifre does not allow direct links between areas of different fuel types. For the conversion of one type of fuel to another, the production units are applied. The production units are depicted by the square in Figure 12. Examples of production units are CHP units, electrolysis, and heat pumps.

The storage units give a more flexible energy flow in the model and make the model less rigid. The triangle represents the storage units. At last is the arrow, which is the analogy for an interconnection line. The interconnection allows the exchange of energy between to areas. The areas must be the same type of fuel; fx heat can not be exchanged with gas. The interconnection lines are mainly used to create an exchange of electricity and gas between the clusters in the European energy system.

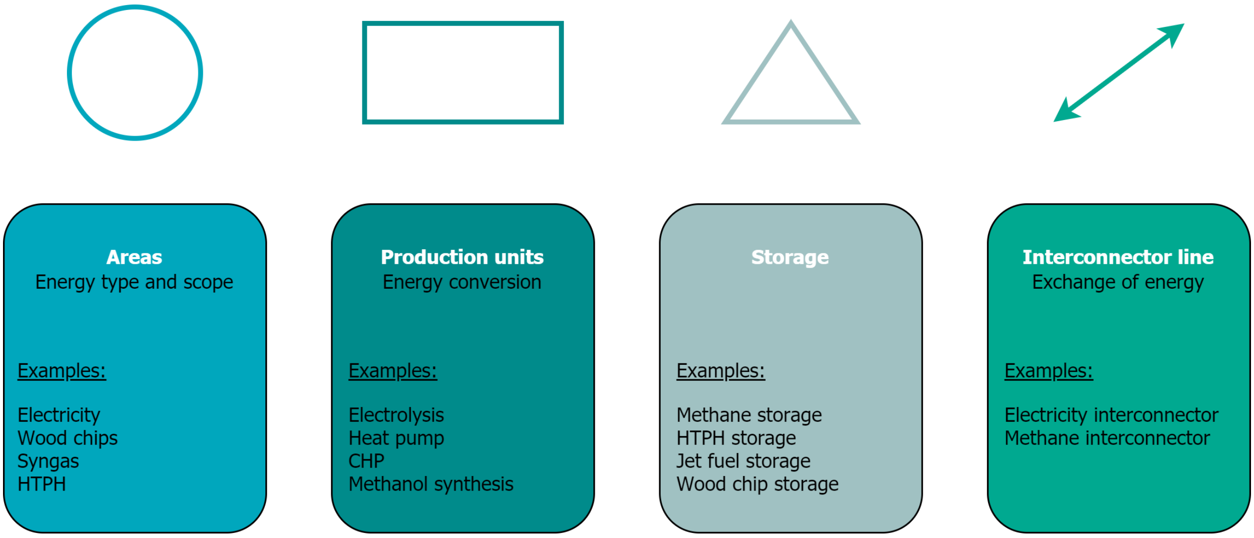

Figure 12: The figure shows the analogies within the Sifre tool with examples of areas, production units, storages, and interconnection lines.

Renewable technologies are the exception for an area to area exchange of energy. The photovoltaic cells and wind turbines are connected directly to an electricity area in the Sifre model. The build-up of renewable production units contains a profile with an hourly capacity factor. The renewable technologies can be curtailed, meaning the unit has the option of producing less electricity than technically possible.

The Sifre model provides an inside to the energy system on an hourly resolution. The Sifre model yields the hourly electricity prices within each cluster. The software can show how it prioritizes production units, fuel types in the transport sector, and the production of renewable technologies on an hourly basis. The simulation tool allows flexibility on consumption, production, energy types, cooperation between energy types, and geography. Sifre meets the demands for simulation of energy systems containing fluctuating energy production from renewable technologies along with the integration of different energy types[28]. Therefore Sifre is an appropriate choice of a simulation tool for modeling the European energy system in this thesis.

The adaptive planning tool, ADAPT, is applied as a build-in option in the Sifre tool. The ADAPT function is a CSV-file, which is loaded into the Sifre tool. The ADAPT tool determines the optimal investment of new infrastructure or technology when given a variety of capacity limits and costs. The ADAPT tool is helpful in scenario analysis of energy systems, as it shows how to priorities capacities. Especially considering energy systems with fluctuating and renewable energy along with storage technology, the ADAPT tool is essential.

5.2 Energy Pathways

This section aims to show the process flow diagrams containing the production units used in the thesis. Each process flow diagram will represent a holistic build-up of each of the five clusters. In order to maintain a simple overview of the interactions of the production units, the process flow diagrams are split into two diagrams. The first diagram provides an overview of the fuel pathways in each cluster. The fuel pathways are shown in Figure 13. For simplicity reasons, electricity and heat flows are not included in Figure 13. Appendix C contains a combined process flow diagram where all interactions can be seen.

In order to read to process flow diagrams, the analogy of Sifre must be explained. Looking at the bar on the top of Figure 13, these are explained. The production unit is applied to convert one type of energy into another. Therefore a production unit must always have both an input and an output. In the case where no input is shown in Figure 13, the input is electricity or heat and, in some cases, both. An area is used in Sifre as an intermediary between the production unit as a resource pool or consumption node. The areas can also be connected to storage units. The flows show how areas and the production units are connected.

Figure 13 shows the conversion of biomass resources to fuels. The anaerobic digestion and thermal gasification processes are prioritized, while direct air capture units produce in case of a shortage of biomass resources. This prioritization occurs due to the cost of the production units (Appendix A.18). Biomass resources are gasified. In the case of wood resources, in this thesis modeled as wood chips, the resources are gasified through a drying, cleaning, and thermal gasification process, which creates syngas. Straw, manure, organic waste, and sludge are all gasified through anaerobic digestion, creating biogas. Biogas is mainly composed of two gasses: methane and carbon dioxide. The path to creating methane from biogas can either be done by stripping the CO_2 from the biogas, releasing it to the surrounding air. The other option is to upgrade the biogas through a methanation process using hydrogen. In terms of transportation applications, methane can be further liquified or compressed to LNG or CNG. Methane is also converted to syngas and hydrogen though steam methane reforming, used in the processes at the bottom of Figure 13. Syngas is used to produce either kerosene (Jet fuel) or methanol. The production of jet fuel is done through a Fischer-Tropsch process, where methanol is a by-product.

Further, methanol can also be produced in the methanol synthesis production unit using

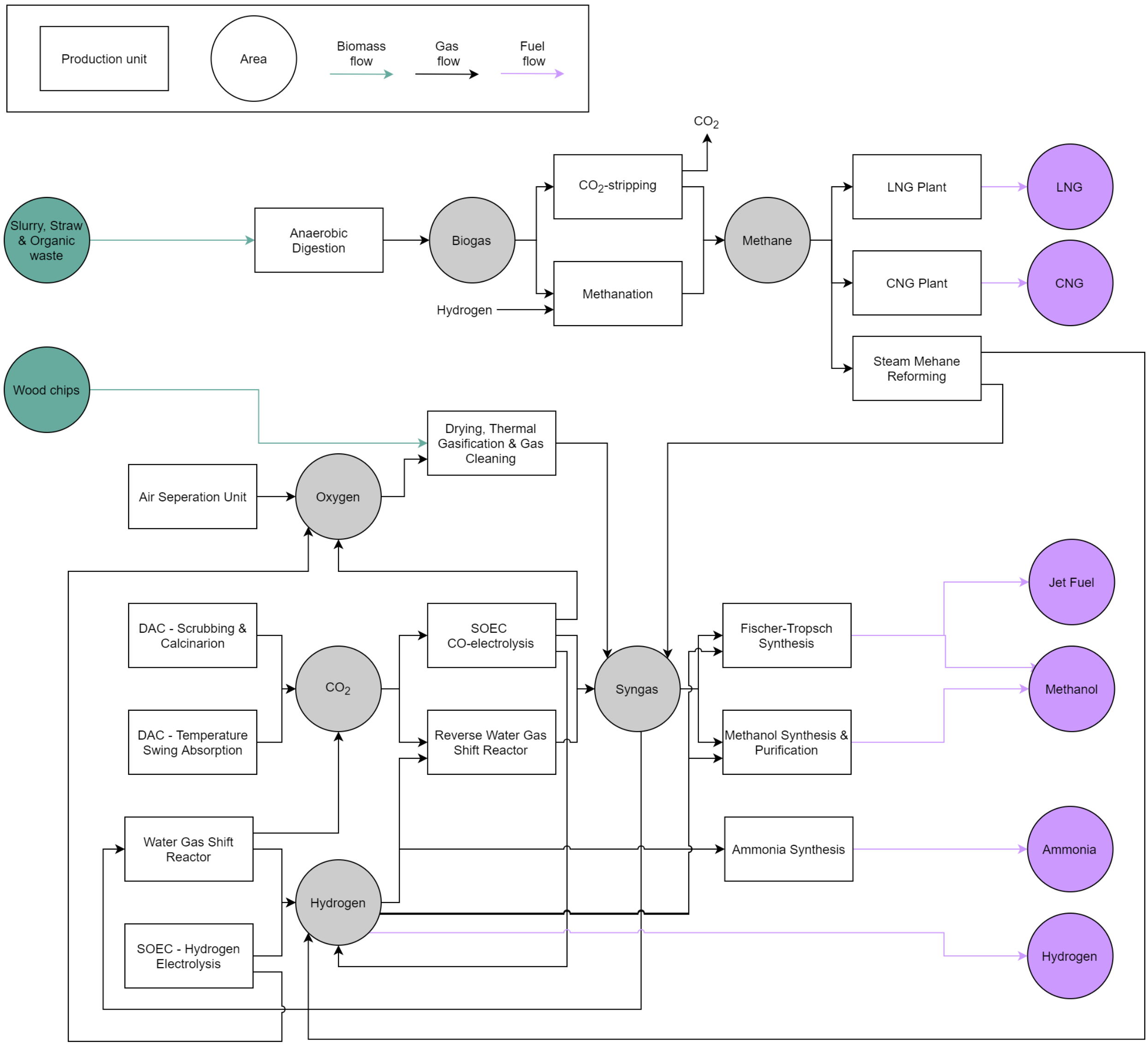

Figure 13: The figure shows the process flow diagram of fuel pathways from Sifre set-up. The figure does not include electricity and heat flows. Detail individual descriptions of processes are in Appendix A.

syngas and hydrogen. Syngas is also an input in a water-gas shift reactor where the production of hydrogen and carbon dioxide occurs. Hydrogen can also be created from the electrolysis process, either from the hydrogen electrolysis unit or the CO-electrolysis unit, which also produces syngas. Hydrogen can be used directly in certain vehicles or be tied to nitrogen, creating ammonia in a synthesis process. Hydrogen can also create syngas in the reverse water gas shift reactor, where carbon dioxide is also an input. CO_2 is extracted from the atmospheric air through direct air capture, DAC. In this thesis, two technologies from DAC are considered.

Figure 14 contains a flow diagram of the electricity and heat pathways used in the Sifre model. The diagram does not contain processes for heat and electricity flows for transportation

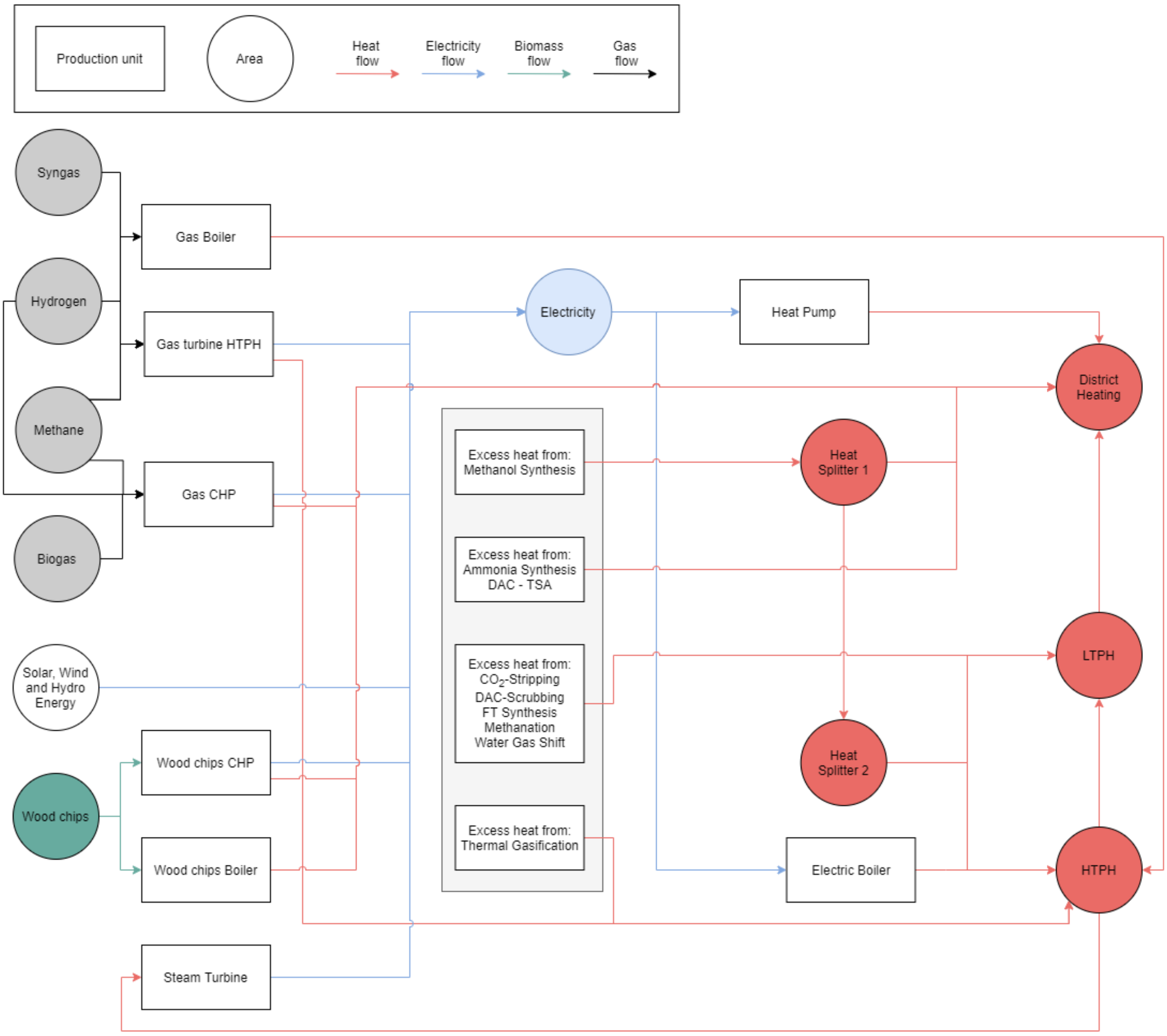

Figure 14: The figure shows the process flow diagram of electricity and heat paths from Sifre set-up. The figure does not include electricity and heat flow for transport purposes. Detail individual descriptions of processes are in Appendix A.

purposes. However, several processes and synthesis within the transportation pathway require high temperatures. In Sifre enables the supply of the residual heat to the heating areas. The grey box in the middle of Figure 14 shows the processes and demonstrates paths to the coherent heating areas, which absorb the residual heat. As mentioned in Section 3, the methodology section, the energy system, is required to be 100% sustainable. The energy-producing units are therefore limited to being carbon neutral. The production units included in the simulation are CHP units, renewable production units, and turbines utilizing the excess high-temperature process heat, HTPH. Either wood chips or gas fuels the CHP units. For the simulation, the gases considered as input in the gas CHP units are biogas, methane, and hydrogen[29]. The use of ammonia in gas CHP units is neglected due to it being an expensive intermediate compared to hydrogen.

The renewable production unit considered for in the thesis includes hydro energy, photovoltaic cells, onshore, and offshore wind turbines. The flow energy units: solar and wind resources are modeled in Sifre by providing capacity factor profiles. The profiles vary depending on the countries. Hence, solar and wind units are modeled on country level[26][12], but supplied to the corresponding clusters. The hydro energy is not a standard feature in Sifre. In appendix B.6, the build-up of the hydro plant is shown. The build-up consists of an area providing water flow to a storage unit. The water from the storage is released to a production unit, which converts the water to electricity. The water flow from the area is season depended. The inflow of water is generally higher in the summer period and lower in winter due to weather conditions. Energinet provides data on yearly hydropower availability.

In the Sifre model, the option of cooling high-temperature process heat to low-temperature process heat and low-temperature process to district heating is included. The connection between these is one way, and can not be reversed without adding energy to the process due to basic thermodynamic principles. The cooling of HTPH and LTPH is free in the model, and there is no limit on the capacity.

The Sifre tool also includes the option of including storage technologies in the simulation. Table 2 shows the storage technologies included in the simulation of the sustainable European energy system. Several of the storage technologies are also included in the ADAPT layer of the model. The storage included are scaled to the efficient economic capacity, which is determined by the investment, fixed yearly cost, and capacity boundaries set in the ADAPT layer. Looking at Table 2, it is evident that the most costly storage technology is the battery technology[30]. The battery technology has the highest investment, and in combination with a low lifespan of the unit, the cost will be significantly higher compared to the other technologies. However, the battery is the only technology, which allows direct storage of electricity. A battery could be preferred over gas storage, as the intermediate process could result in higher prices. Generally, the gas storage technologies are significantly cheaper, especially the biogas and ammonia storage[30].

The greyed storage technologies in Table 2 represent the storage technologies not included in the ADAPT layer. The storage technologies are included as buffers in the simulation to provide flexibility in fuel consumption and production. The fuel availability in Sifre is set with a fixed hourly inflow[2]. The flexibility of fuel consumption is crucial. Therefore the fuel inflow is fed to storage instead of directly to the production units. The fuels consumed in the transport sector, e.g., jet fuel, have storage units to ensure flexible production. The use of fuel storage can also lower the price of output fuels due to production in hours with lower electricity prices. Electricity is an input in the majority of the production units creating gases or fuels. Methane storage is greyed out since it is assumed the storage technologies are available, and no further investment is needed.

Table 2: The table shows the storage types considered in the model. The models included in the ADAPT investment tool have cost of these included in the model[30]. The rest are used as buffers for fuels and are made to enable optimized used or production, with an economic perspective.

Storage	**Marginal Investment [EUR/MWh]**	**Fixed O&M [EUR/MWh]**	**Interest rate [Pct.p.a.]**	**Lifespan [Year]**
Ammonia	670	0	4	20
Battery	100.800	0	4	12
Biogas	670	0	4	20
DH	2.300	0	4	30
HTPH				
Hydro				
Hydrogen	3.300	0	4	30
Jet Fuel				
LNG				
Methanol				
Methane				
Organic Waste				
Oxygen	381.720	0	4	25
Sludge				
Slurry				
Straw				
Syngas	80.00	0	4	30
Wood chips				

5.3 Simulation Scenarios

Based on the knowledge of the options in the simulation tool along with the energy demand and fuel availability presented in Section 4 several scenarios are developed in the Sifre tool. All scenarios have the same demand and biomass resource availability. However, the four scenarios revolve around adjusting the availability of solar and wind energy along with changing interconnection capacity.

The first scenario is the base scenario. The base scenario applies all data represented in previous sections of the thesis. Figure 15 shows a simple build-up of the four scenarios. All scenarios have the same biomass resource input and pathways for electricity, heat, and transportation fuels, hence they are not included. The base scenario in Figure 15 shows the limited capacity of renewable energy, and interconnection capacity is restricted to currently planned capacity by 2050. The interconnection capacities are found through the ENTSO-E/G energy map[19] along with reports published by the TSOs of relevant countries and the Nordic Grid Development report[20][21]. There is no gas trade between West and North Europe. The TYNDP20 report provides limitations on renewable energy capacities[12].

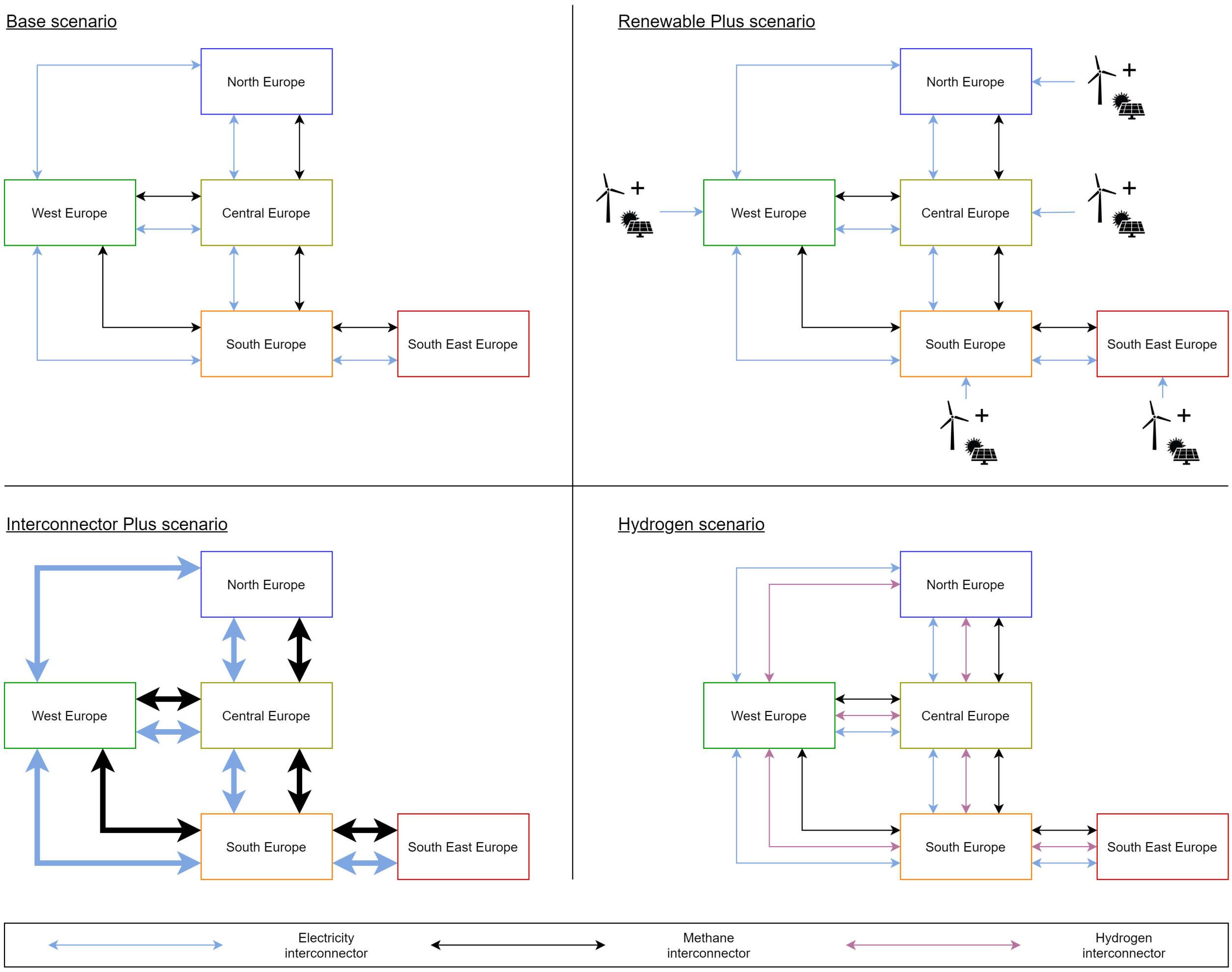

Figure 15: The Figure shows a simplified representation of the four scenarios considered in the thesis. The baseline capacity of interconnectors across the clusters are in appendix C.2.

The renewable plus scenario removes the limitation on the capacity of renewable energy. The goal of the scenario is to find the optimal invested capacity of photovoltaic cells and wind turbines, without considering the limitation of land to be exercised for renewable production units. In the article "The European Electricity Market and Cross-Border Transmission," written by M. Adamec [31], he discusses how Europe might be in shortage of electricity in the future. The scenario aims to improve internal capacity in each cluster. By increasing renewable capacity, it is expected the production of hydrogen, among others with be carried out more efficiently with lower electricity prices. The interconnection capacity remains the same, and the gas trade between the North and West Europe remains zero. The scenario seeks to improve internal production rather than improving trade between clusters.

The interconnection plus scenario emphasizes trade between clusters across Europe. Throughout the years, the interconnector capacity has improved and continues to do so in the future[19]. With more intermittent electricity services, the need for backup has increased along with options to trade excess electricity in hours with electricity production for intermittent producers. The scenario will investigate the effect of improving the capacity of methane and electricity trade throughout Europe. The thesis investigates to which extent increasing interconnector capacity will improve conditions in a sustainable energy system. The expectation is to enable more flexible production of hydrogen and electrofuels along with increasing security of supply and thereby lowering the need for backup capacity in the form of CHP units. The Sifre model is altered to allow a maximum of 100 GW capacity through the interconnector lines shown in Figure 15. The renewable capacity available changes back to the recommendations of the TYNDP20 report[12].

Lastly, the possibility of allowing the trade of hydrogen across Europe is investigated. Including interconnectors containing hydrogen will allow hydrogen to be produced in the cluster with the lowest electricity price. Hydrogen interconnectors are an alternative to exporting cheap electricity to a high price cluster and produce hydrogen locally. Enable hydrogen interconnectors is done with the expectation of lowering the cost of hydrogen throughout Europe. Hydrogen is expected to increase in importance as Europe becomes more sustainable and can be applied in both the electricity, heating, and transport sector[32][33]. In the electricity and heating sector, hydrogen is a fuel in the CHP and boiler units. In the transport sector, hydrogen is used in fuel syntheses along with fuel directly in road transport.

Trade of hydrogen is a much-discussed topic as it has some technical obstacles. The greatest obstacle related to the trade of hydrogen is the embrittlement effect. Hydrogen embrittlement occurs because of the size of the hydrogen atom relative to the molecular structure of the material containing it. The hydrogen atom migrates into the crystal lattice of the containing material, increasing the stress on the material. If sufficient hydrogen migrates into the material, the material can fracture due to high stress[34]. A solution to this is to bake the material at 220 °C for 4 hours within 1 hour after plating. The heat will allow natural present hydrogen to be removed from the material [35].

As a result of the issues related to the trade of hydrogen, the price of hydrogen interconnectors are higher compared to conventional gas interconnectors[22]. However, the energy density of hydrogen is above twice the energy density of methane, making hydrogen a more energy-dense fuel to transport across Europe. If hydrogen is produced flexible, it might also have a lower price compared to methane[32][33]. In the hydrogen scenario, the production of electrofuels is expected to be done more efficiently and lowering the prices of electricity, as the demand for electricity for electrolysis units can be shifted across Europe.

6 Discussion and Interpretation of Simulation Results

Based on results obtained through the Sifre model and the ADAPT investment optimization, several findings are analyzed and will be presented in this section. The interpretation of the results presented will include comments on flexibility in the system, the security of supply in the energy sectors along with bottlenecks in the system, and overall energy flows. At the end of this section, the socio-economics of the systems are presented, and an evaluation of both the economic and technical specifications is conducted.

Sankey diagrams will serve as a guide throughout this section. The Sankey diagrams are used for the interpretation of prioritization of production in the energy system for each cluster in the four simulation scenarios. Throughout discussion topics, references to the Sankey diagrams are made. Figure 16 shows the operation of the northern cluster in the renewable scenario. Sankey diagrams for all clusters in all scenarios are in Appendix E.

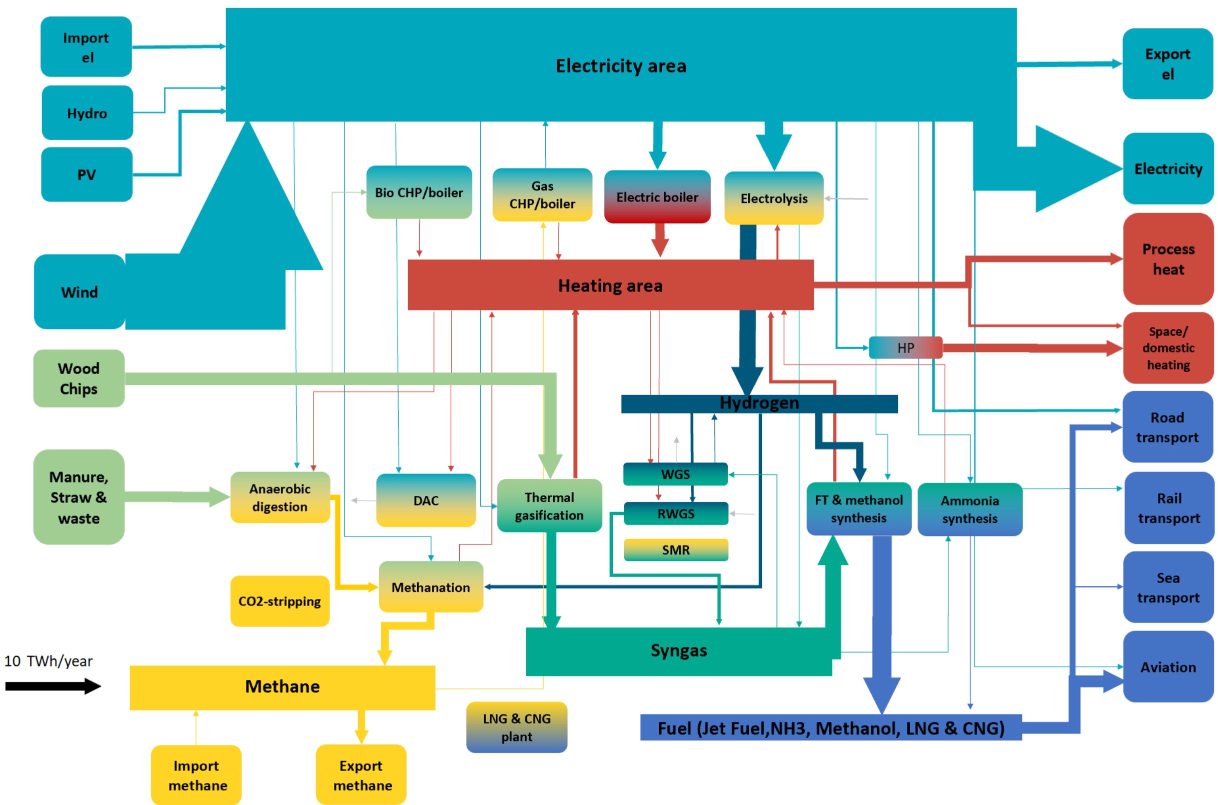

Figure 16: The figure shows the Sankey diagram of the northern energy system in the renewable plus scenario. The northern energy system is mainly supplied with wind energy resources.

In the top left of Figure 16, the inflow of renewable electricity producers are shown along with imported electricity from neighboring clusters. From the Sankey diagram, it is evident that the leading electricity supplier in the northern cluster is wind turbines. The northern cluster also appears to export more electricity than is imported.

The biomass supply is divided into two paths. Manure, straw, organic waste, and sludge serves as input in the anaerobic digestion process creating biogas. The anaerobic digestion removes impurities from the gas[18], and clean biogas is transferred further in the system. Biogas consists of both CO_2 and CH_4, the CO_2 is removed from the biogas to methane. Two methods for upgrading biogas to methane are considered. The first method is to strip the biogas from CO_2 and releasing the CO_2 to ambient air[36]. The second method is to add hydrogen, which will react with the CO_2, creating additional methane, oxygen is released to the ambient air in this process[37]. The methanation process is more expensive and requires hydrogen to be available. In the renewable scenario for the northern cluster, hydrogen is available due to high electricity production from intermittent electricity suppliers. Therefore biogas is upgraded with hydrogen in this scenario in the northern cluster. Methane is either applied in the gas boiler and CHP unit for the production of LNG/CNG or the steam methane reforming process, creating syngas[38][39].

The second biomass path is for the dry biomass. Wood chips are gasified in the thermal gasification process creating syngas[2]. The process occurs at a high temperature, and excess heat from the process is supplied in the heating area. The thermal gasification process has higher investment and operation cost compared to the anaerobic process (Appendix A.18). Wood chips can also be applied directly in the bio CHP and boiler units for heat and electricity production. In Figure 16, wood chips are supplied to the bio boiler, creating heat for the heating area. Syngas from the thermal gasification process can be used in fuel production along with the water gas shift reactor creating hydrogen and CO_2[2]. Syngas can also be used in the gas boiler. Syngas is mainly used in fuel synthesis in Figure 16.

The main electricity supply is for the electricity sector. Figure 16 shows that a significant amount of electricity is consumed for heat production in the electric boiler and hydrogen production in the electrolysis unit. The electric boiler and electrolysis unit are expected to be consuming electricity in hours with excess electricity from intermittent electricity producers. Heat pumps are also consuming electricity for the production of space and domestic heating.

Direct air capture, DAC, is rarely used in the northern cluster in the renewable scenario. DAC captures CO_2 from ambient air[40][41]. The CO_2 is used in the Co-electrolysis unit or the reverse water gas shift reactor for the creation of syngas[42]. The Co-electrolysis produces syngas alongside hydrogen[43]. The production of syngas through electrolysis in the northern cluster is rather small, as the wood chips supply sufficient resources to the syngas area. Steam methane reforming is not used in the north cluster in the renewable scenario. The process enables the production of syngas and hydrogen using methane as an import. In the northern cluster, most of the methane is exported rather than used locally.

The fuel syntheses are shown in a simplified version in Figure 16. The Sankey diagram divides fuel syntheses into two processes. The first is the Fischer-Tropsch process and the methanol synthesis. Production of jet fuel alongside methanol occurs in the Fischer-Tropsch process[2]. The methanol synthesis produces methanol[2]. Jet fuel is consumed in the aviation sector; methanol is consumed in the road, sea, and rail transport sector. In the sea sector, the option of using ammonia as fuel is included. The ammonia produced is shown in the ammonia synthesis process[44].

6.1 Generated Prices and Distribution of Electricity Services

This section investigates the hourly electricity prices within the five European clusters across the four scenarios stated in Section 5.3. The aim is to obtain an insight into the performance of each cluster under the circumstances of the four scenarios and see how changing production capacity along with trade options between clusters affect the electricity prices in the five clusters.

This section will also comment on the methane and hydrogen price in each of the four scenarios in the five clusters, respectively. Appendices D.1 through D.8 contain duration curves for hourly methane and hydrogen prices in all four scenarios. Comments on the pattern interpret if the tendencies of the electricity price correspond with the hydrogen and methane prices.

6.1.1 Electricity Prices for the Base Scenario

The first section will investigate the electricity price across the five clusters for the base scenario. The base scenario provides an insight into the European energy system in a "business as usual approach," meaning with currently recommended capacities. For the base scenario, the capacity of renewable energy is restricted to the recommendations of the TYNDP20 report[12]. These restrictions were examined in Section 4.2.5. Levels of trade of electricity and methane between the clusters are also restricted to current levels, including interconnectors planned for commissioning before 2050[19]. The base scenario also has the biomass availability presented in Section 4.2, which results in limitation on resources in the electricity sector along with the heating and transportation sector.

The base scenario generally encounters several obstacles. Being a quite restricted-energy system, the flexibility in the production of cheap electricity is limited. Due to the lower availability of solar and wind energy along with restricted trade possibilities, it increases the need for backup capacity in the form of battery storage, along with gas and biomass CHP capacity. However, the availability of biomass resources is also restricted, making the production of electricity through biogas or biomass difficult. The amount of residual electricity available for producing synthetic gas and hydrogen is too limited, making the overall energy system quite rigid across all five clusters.

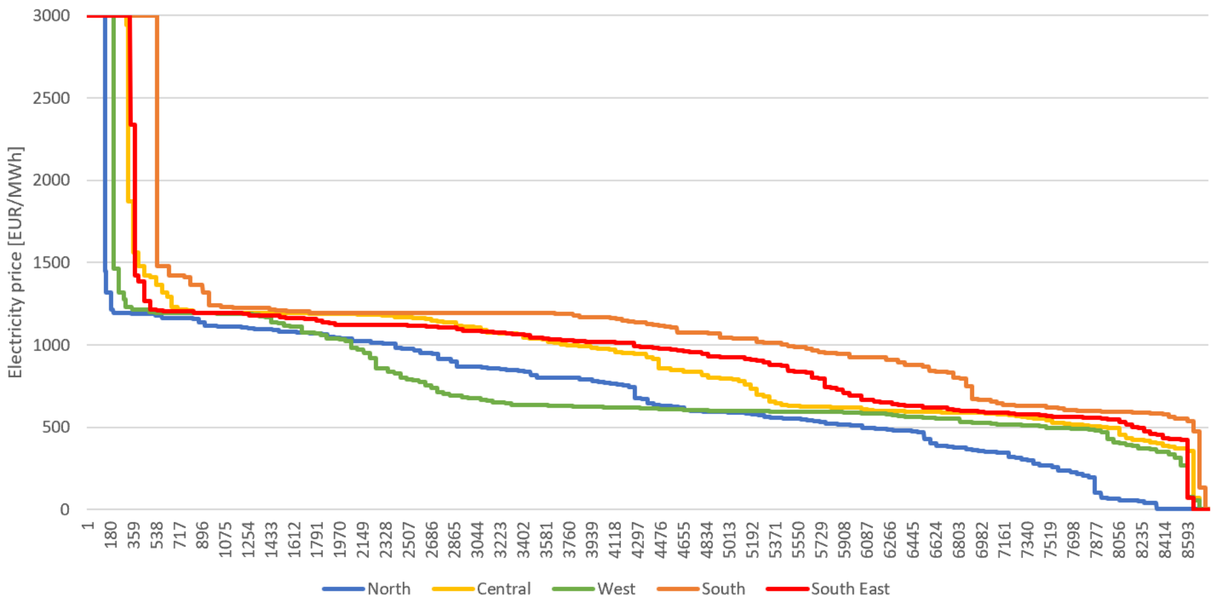

Figure 17: The figure shows the hourly electricity price for the five clusters in the Base Scenario. The electricity prices are plotted as duration curves.

Looking at Figure 17, it is evident the electricity prices in the base scenario are generally quite high, with average prices varying between 700 to 1000 EUR/MWh depending on the cluster. The reason for the high prices is expected to be the restriction on the availability of resources and trade possibilities. However, the consequences of the shortage of resources available do not affect the clusters equally. The northern and western clusters show significantly better performance compared to the other cluster. This might be given by looking at Table 1 in Section 4.3. Looking at the table, it is clear that North and West Europe are more resource strong clusters. Especially North Europe, with high availability in wood resources along with wind and hydropower and combined with low demand due to being a quite population sparse cluster, has greater opportunities for more flexible production. The north cluster is the only cluster, which does not use all the wood resources in the thermal gasification process (Appendix E.1). Excess wood resources can, therefore, be used in the CHP unit in peak hours with low availability of wind and solar power. The northern cluster is the least rigid cluster. The higher flexibility results in it having the lowest electricity prices, with only a few hours where the western cluster have lower electricity prices.

The southern clusters have the highest electricity price in the base scenario. The high price can be reasoned by being in the opposite situation of the northern cluster. The southern cluster is population-dense and has a more substantial demand, but fewer resources available. As a consequence, the energy system of the southern cluster is very rigid. The availability of residual electricity for electrolysis is almost not present, and the production of hydrogen is not produced with residual electricity. The southern cluster imports methane for gas CHP and imports electricity to have sufficient amounts to meet the conventional demand and produce hydrogen for electrofuels. The hydrogen is very scarce in the southern cluster. As a result, the southern cluster does not upgrade the biogas. The biogas is instead stripped from carbon dioxide, resulting in the biomass resources not being utilized fully.

The central and southeastern clusters are also quite rigid and have high electricity prices. The central cluster also has a high demand. However, it is less resource-scarce compared to the southern cluster. The southeastern cluster has the lowest demand for electricity in all the clusters. However, the electricity price is high, and the reason could be the trade pattern between South Europe and South East Europe. The southeastern cluster has to increase the production of electricity to cover the demand of the southern cluster.

The lower electricity price in the northern cluster is directly reflected in the hydrogen price within the cluster. Looking at Appendix D.5, it is evident that the hydrogen price within the northern cluster is significantly below the other clusters. The lower northern hydrogen price is explained with the flexibility in the northern cluster, where hydrogen is not produced when needed but is more likely to be produced when excess electricity is available. The other clusters have more similar hydrogen prices, and prices are generally high. The shape of the duration curve for these clusters does not show any pattern yielding the flexible production of hydrogen.

Appendix D.1 yields the methane price to be the same in all clusters and generally high. There is no evidence of the flexible production of methane in any of the clusters. The price of methane is affected by the electricity price, as electricity is applied in the CO_2-stripping and methanation process.

6.1.2 Electricity Prices for the Renewable Plus Scenario

As an extent of the base scenario, the capacity of renewable energy is scaled up in the renewable plus scenario. The base scenario appeared to be rather stiff; the purpose of the renewable plus scenario is to create a more flexible energy system. The boundaries on biomass resources and trade possibilities remain restricted. The scenario increases the renewable capacities without consideration of land occupation of wind turbines and photovoltaic parks. The scenario investigates the operation of an energy system with an abundance of renewable capacity.

Compared to the base scenario, the performance of the renewable plus scenario is significantly improved. The amount of surplus electricity, which can be applied in the electrolysis process, is increased. Therefore hydrogen is produced more flexibly and at lower prices in the renewable plus scenario compared to the base scenario. Syngas can also be produced cheaper in the renewable plus scenario through electrolysis in clusters with low availability of biomass resources. Lastly, the biogas in the clusters can also be upgraded using hydrogen, further in this scenario compared to the base scenario.

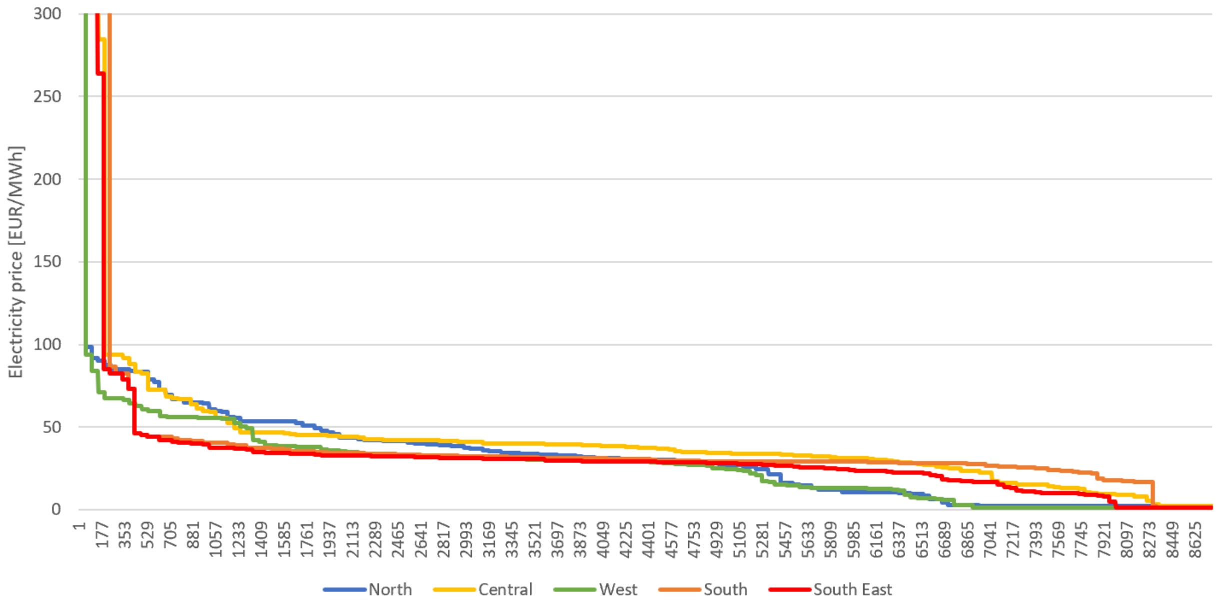

Figure 18: The figure shows the hourly electricity price for the five clusters in the Renewable Plus Scenario. The electricity prices are plotted as duration curves.

Figure 18 shows the electricity prices of the five clusters plotted as a duration curve. When looking at the electricity prices, it is noticeable the electricity prices are significantly lower compared to the base scenario. The average price of electricity varies between 30 and 50 EUR/MWh depending on the cluster. Hence the electricity price has improved by factor 20 in some clusters. The electricity price has especially improved in the south and southeastern cluster, where the electricity price is well below 50 EUR/MWh in most hours throughout the year. The renewable plus scenario enables larger electrolysis capacity and a more flexible production of hydrogen.

The northern cluster has some peak hours where the electricity price is higher compared to the other clusters. The southern cluster has higher electricity prices in the hours with otherwise low electricity prices. However, Central Europe is the cluster with the highest average electricity price. Central Europe has the second-highest electricity demand of the clusters. A combination of high demand and a restriction on interconnection capacity does make Central Europe more dependent on storage and gas CHP capacity, which are more expensive technologies. The use of CHP capacity is evident when comparing the Sankey diagram for the clusters in the renewable plus scenario (Appendix E.6 to E.10). The northern, western, southern, and southeastern cluster does all have lower use of CHP compared to the central cluster.

The northern and western clusters show the lowest electricity prices. The pattern is similar to the base scenario, where these clusters also showed the lowest prices. The scaling up of renewable capacity does allow high electricity production through solar and wind resources. The increase in intermittent electricity services does improve the production of hydrogen and thereby also allows significantly more biogas to be upgraded using hydrogen. The upgrading of biogas using hydrogen results in the higher utilization of biomass resources. The higher availability of methane is especially evident in the northern cluster, where the hydrogen production increase enough to upgrade all biogas in the northern cluster (Appendix E.6).

As established in the base scenario, the price of hydrogen is greatly dependent on the price of electricity. It is extremely beneficial to produce hydrogen in hours with low electricity prices due to residual renewable electricity. The renewable plus scenario is, therefore, also the scenario with the lowest price of hydrogen across all clusters (Appendix D.6. The price drop of hydrogen compared to the base scenario is very similar to the drop in electricity between the two scenarios. The hydrogen price drops with approximately a factor 20 compared to the price of hydrogen in the base scenario. The price of hydrogen is quite similar in the five clusters. However, it is a bit lower in the western and northern cluster.

The price of methane also drops significantly compared to the base scenario. Looking at Appendix D.2, the price of methane is below 50 EUR/MWH in most hours through the year in all five clusters. The price of methane does not change greatly, depending on the cluster. The overall drop in the electricity price does appear to have had a very positive effect on the methane price. Another explanation can be the drop in the use of methane in gas CHPs across the clusters, which has decreased the demand for methane and thereby decreased the price.

6.1.3 Electricity Prices for the Interconnector Scenario

Another route to improve the performance of the base scenario is to increase the interconnector capacity between clusters. The interconnector scenario relief restrictions on the traded capacity of methane and electricity. The restrictions on biomass and renewable resource are the same as in the base scenario. The purpose of this scenario is to investigate the performance of allowing free trade between the clusters.

Compared to the base scenario, it is evident that lowering restrictions on interconnector capacity improves the electricity price notably. Hours with a scarcity of electricity in the clusters are lower due to the support of electricity production from the surrounding clusters. The improved trade options of methane can further reinforce electricity production through gas CHPs along with the production of hydrogen and syngas through electrolysis. However, the performance of the interconnector scenario does not perform remotely as well as the renewable plus scenario. The interconnector scenario is, as the base scenario, rather rigid due to the lack of surplus electricity. The lack of residual electricity lowers the opportunity for flexible production of hydrogen and syngas.

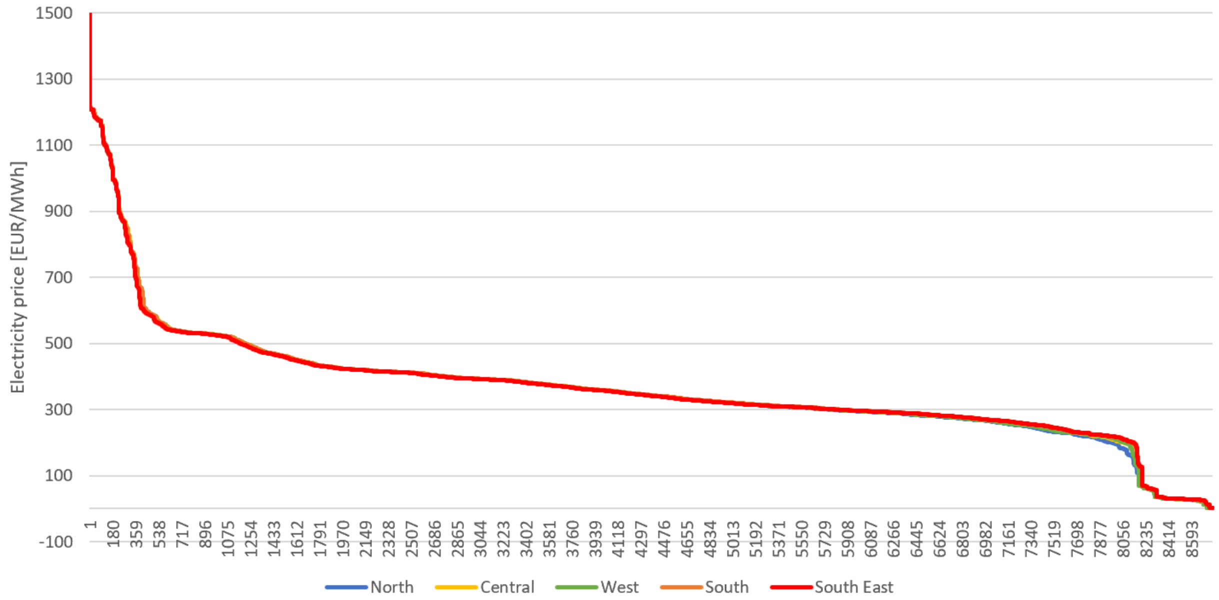

Figure 19: The figure shows the hourly electricity price for the five clusters in the Interconnector Scenario. The electricity prices are plotted as duration curves.

Looking at Figure 19, it can be interpreted that allowing free trade of methane and electricity between the cluster makes the electricity price almost uniform across Europe. The electricity price is lower in the interconnector scenario compared to the base scenario. The yearly average electricity price in the interconnector scenario is 360 EUR/MWh. Thereby the electricity price is halved for some clusters and, in other cases, even more. Having equal electricity prices across Europe is an indicator that the bottlenecks in the system are gone, and power can flow freely across Europe[45]. Increasing interconnector capacity is especially beneficial for the central, southern, and southeastern cluster, where the electricity in the base scenario was rather expensive throughout the year. However, the prices are also significantly lower in the northern and western cluster.

Figure 19 reveals a slight drop in electricity prices in the last approximately 400-500 hours. In these hours, the price is similar to the prices shown throughout the year in the renewable plus scenario. These hours are also optimal for hydrogen production; however, to improve conditions for flexible hydrogen production, the number of hours must be increased.

Appendix D.7 reveals a drop in hydrogen prices compared to the base scenario. The price of hydrogen in the interconnector scenario resembles the prices in the base scenario, where the northern cluster has significantly lower prices compared to the other clusters. This divergence in price could indicate a more significant amount of excess electricity for hydrogen production in the northern cluster, which lowers the hydrogen price generally in the northern cluster.

The methane prices do also benefit from the lower electricity price in the interconnector scenario (Appendix D.3). The methane price has dropped significantly, especially during peak hours. The decrease can be explained by generally lower consumption of methane in CHP boilers along with lower prices of electricity for upgrading biogas through CO_2-stripping and methanation using hydrogen.

6.1.4 Electricity Prices for the Hydrogen Scenario

The last scenario does not adjust to any existing capacities in the base scenario but offers a new interconnector option between the cluster. In the hydrogen scenario, it is researched whether trading hydrogen is beneficial across the clusters. Six bidirectional hydrogen interconnectors are modeled in the Sifre tool, each with a maximum capacity of 10 GW, these are connected between neighboring clusters. The purpose is to explore the performance of the European energy system with the possibility of producing hydrogen and export it. Allowing trade of hydrogen between clusters enables closer to equal availability of hydrogen, which can be used in CHP units and for fuel production for the transport sector.

Comparing the base scenario and hydrogen scenario, it is evident the electricity price decreases. Being able to trade the hydrogen across clusters results in less stiffness in the clusters with lower quantity residual electricity, as the clusters can receive hydrogen in the system without having to produce it themselves. Likewise, the clusters with more excess electricity can utilize this in the electrolysis process rather than curtail the electricity production from wind turbines and PVs.

Figure 20 reveals implementing the options of trading hydrogen across the clusters as a beneficial solution. The electricity price drops compared to the price in the base scenario; however, implementing hydrogen interconnectors is not equally beneficial for all clusters. The yearly average electricity price varies between approximately 330 and 475 EUR/MWh depending on the cluster. When comparing with the interconnector scenario, the hydrogen scenario is more beneficial for the northern and western clusters. However, in the central, southern, and southeastern clusters, the electricity price is lower when lifting restrictions on methane and electricity interconnector capacity.

The price difference between the clusters does imply that bottlenecks are present in the

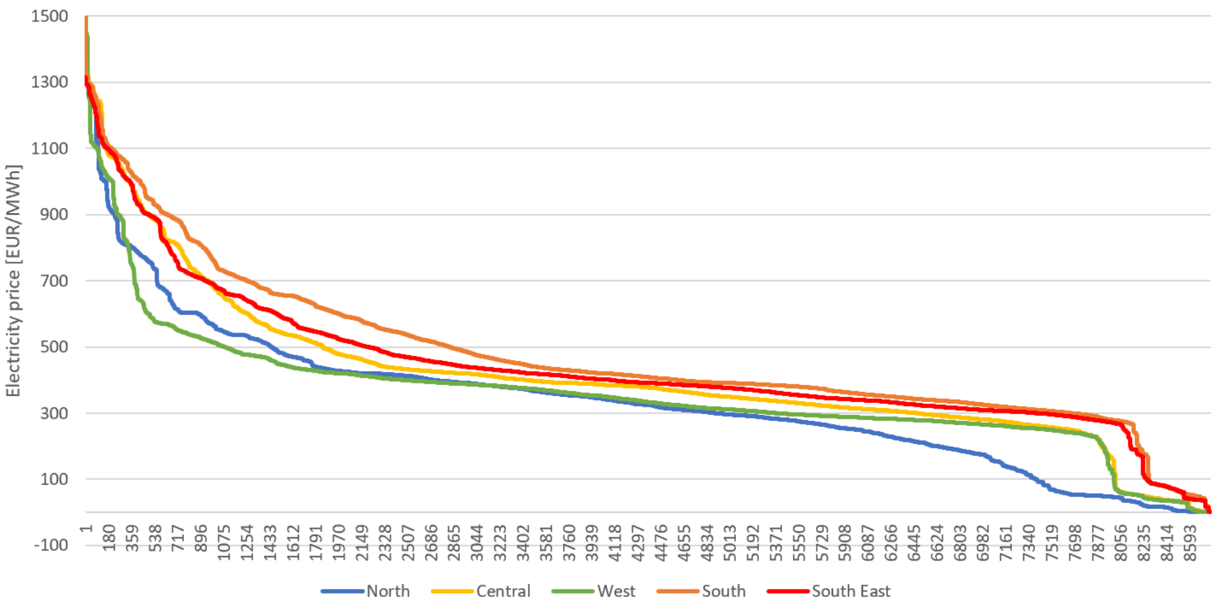

Figure 20: The figure shows the hourly electricity price for the five clusters in the Hydrogen Scenario. The electricity prices are plotted as duration curves.

energy system. The bottlenecks occur due to the difference in renewable energy in different clusters and restrictions on interconnector capacity[45]. The northern and western cluster does have more renewable energy available, and with limitation on the trade of electricity to neighboring clusters, the price difference occurs. In the hydrogen scenario, the clusters do have the option of producing additional hydrogen through electrolysis and do not curtail the renewable energy to the same extent as in the base scenario(Appendices E.16 and E.18).

The hydrogen scenario does not offer electricity prices at the same level as in the renewable plus scenario. The northern cluster appears to be the cluster with the lowest electricity price and has dropped in the last 1000 hours in Figure 20, where the price resembles the price level in the renewable plus scenario. The southern and southeastern clusters are the clusters with the highest electricity prices, mainly due to resource scarcity in these clusters and the case of the southern cluster combined with high demand. The western has lower prices during peak hours. The low prices can be explained by a combination of having methane resources for gas CHP units and being located conveniently with trade options both to the north, central and southern clusters.

The hydrogen prices follow the electricity prices for the hydrogen scenario. Appendix D.8 reveals the northern cluster to have significantly lower hydrogen prices compared to the other clusters. The central and western clusters have a similar price level. The southern and southeastern clusters have a slightly higher price level. The hydrogen prices are generally high in the hydrogen scenario and appear to be higher compared to the interconnector and renewable plus scenario in all clusters. The hydrogen price is lower in the northern cluster in the hydrogen scenario compared to the interconnector scenario in the low price hours. The northern hydrogen price follows the trend in the electricity price for the northern cluster, where a drop is also present.

The methane price is slightly higher in the hydrogen scenario compared to the interconnector scenario. However, significantly lower compared to the base scenario. Appendix D.4 shows that the price of methane is uniform across the clusters. The demand for methane in the gas CHP decreases in the hydrogen scenario compared to the base scenario, but is higher compared to the interconnector and renewable plus scenario, and explains more expensive methane in the hydrogen scenario. This low availability of electricity results in a lower amount of biogas being upgraded using hydrogen. When less biogas is upgraded with hydrogen, methane is more scarce and creating another reason the price increases.

6.1.5 Comparison of Electricity Distributions Across Clusters and Simulation Scenarios

From the duration curves of electricity prices, it can be gathered the renewable plus scenario offers the best condition to lower electricity prices and more flexible production. The interconnector scenario made conditions across Europe equal. However, the price of electricity is significantly higher compared to the renewable plus scenario. The base scenario is the scenario with the highest electricity prices throughout Europe. Hence all adjustments made in the subsequent scenarios improved the electricity price.

Figure 21 shows the distribution of energy services in the electricity area, depending on the cluster and scenario. Looking at Figure 21, it is evident that electricity is mainly supplied from renewable energy technologies. Renewable energy technologies are cheap in operation costs and, as a result, higher implementation of these lower the electricity price. The prices increase when starting up backup capacity in hours where intermittent electricity suppliers do not meet the demand. The backup capacity consists of gas and biomass CHPs along with the utilization of excess process heat (300°C - 1000°C) and, to the extent, water is available, hydropower.

Looking at Figure 21, it can be seen the need for expensive backup capacity, e.g., CHP and HTPH turbine, is more significant in the hydrogen and base scenario. These scenarios offer limited trade capacity and restrictions on investment in renewable capacity. As a consequence the cost of production of electricity increases. The hydrogen scenario does provide less need for backup capacity. This could be explained by the option of trading hydrogen between clusters, which can lower the need for electricity supply for electrolysis, making the demand for electricity lower and release more capacity in electricity storage (Appendix D.9). Generally, the need for battery storage

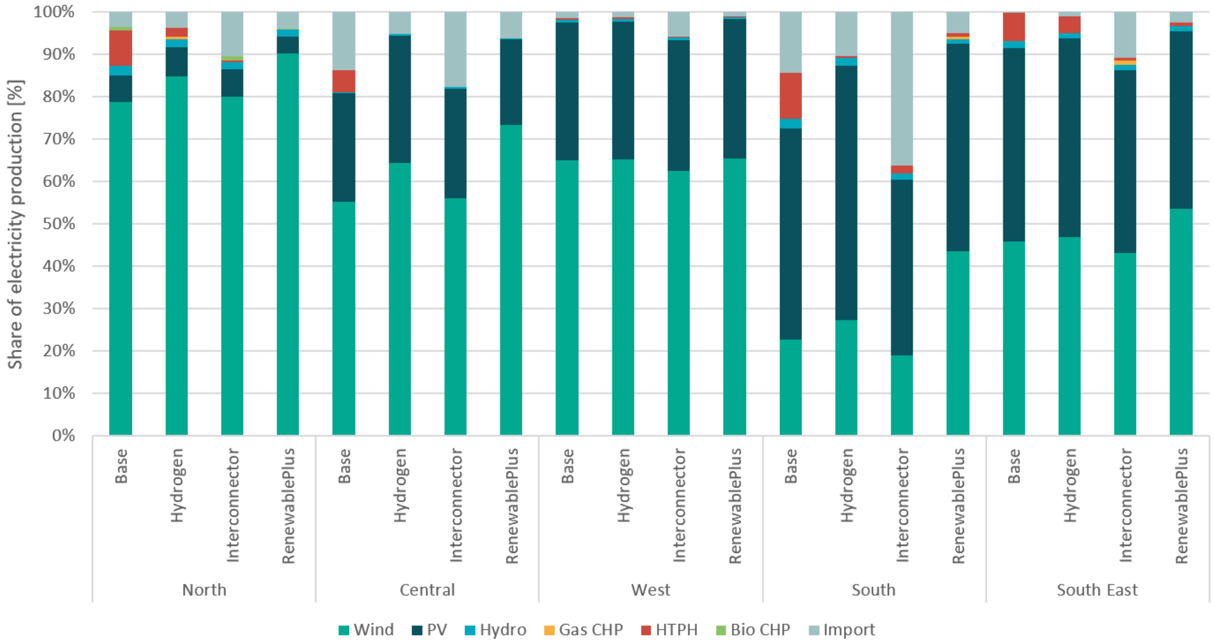

Figure 21: The figure shows the distribution of technologies applied for the production of electricity in each of the five clusters in the four scenarios.

is higher in the base and hydrogen scenario, as the clusters are more self-depended and restrictive. The battery is rather expensive, and in the renewable plus and interconnector scenarios, it is shown to be less vital.

The renewable plus scenario decreases the need for backup capacity, and in the case of the western cluster, it has shrunk to close to nothing. In the renewable plus scenario, intermittent power producers are available in abundance. In hours with insufficient wind or solar resources, the backup capacity used is preferably interconnector lines more than CHPs and HTPH turbines. To further extent, compared to the other scenarios, wind and solar energy production is curtailed in the renewable plus scenario in hours with overproduction.

The interconnector scenario also lowers the need for backup power producers. By having free trade between the clusters, the need for CHPs and HTPH turbines decreases. In the case of the central and western clusters, the backup is limited to almost none. The graphical location of clusters can explain the lower need for backup capacity. Moreover, in the western cluster, further explained by high local production. The southern cluster, too, has a good location, as it has three neighboring clusters. However, the southern cluster has limited local production and relies greatly on trade with neighboring clusters.

6.2 Fuel Distribution and Yearly Investment Cost

The distribution of the energy added to the energy system differs across clusters and scenarios. Depending on the distribution of these, the yearly investment costs in the cluster differ. This section seeks to interpret correlations between yearly investment cost and the distribution of energy services and fuel inflows in the energy system. The variance in the population density changes the demand in the clusters. Therefore, the yearly investment cost is given per person, enabling comparison between clusters. The fuel inflows are divided into wet and dry biomass. The dry biomass is wood chips, which are applied in the thermal gasification process. The wet biomass is manure, sludge, straw, and organic waste, which are all utilized for biogas production through anaerobic digestion. The renewable electricity suppliers included are wind turbines, photovoltaic cells, and hydropower.

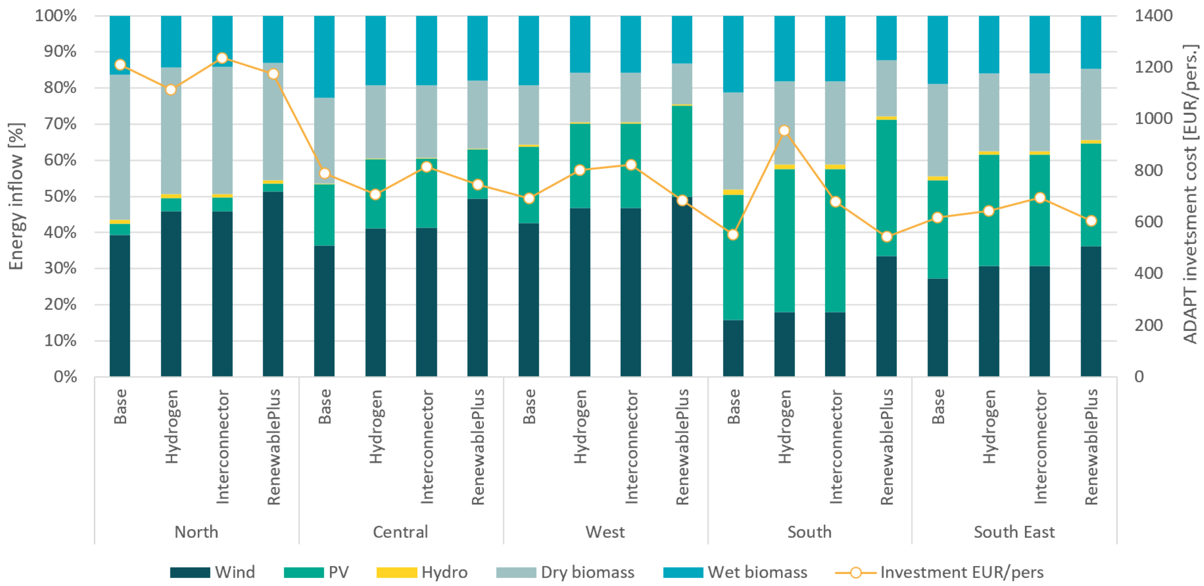

Figure 22: The figure shows the fuel inflow and yearly investment costs across Europe in the four scenarios. The inflow in the energy system consists of renewable production units along with biomass resources. The wet biomass is used in the anaerobic digestion process. Dry biomass is used in the thermal gasification process, along with bio CHP and boiler units. The yearly investment cost is given per person in the clusters.

Figure 22 is a graphical representation of the inflows to the energy system and the coherent investment cost. From the interpretation of the figure, it can be concluded that the northern cluster is the cluster with the highest portion of dry biomass. The dry biomass is converted to syngas in the thermal gasification unit. The process has a rather high investment cost and could be the reason the northern cluster has significantly higher investment costs compared to the other cluster throughout the scenarios. The investment cost decreases in the hydrogen scenario, and the renewable share increase, mainly to the option of exporting hydrogen and thereby utilize more renewable production, which would have been curtailed. In the interconnector scenario, the investment increases and is the highest of all four scenarios for the northern cluster. The increase is due to higher production. In the renewable plus scenario, the investment is decreased, and the share of renewable resources is increased.

In the central cluster, the share of wet biomass is higher compared to the northern cluster. The higher share of wet biomass versus dry biomass seems to decrease the investment in Central Europe across all the simulation scenarios. The central cluster also has a higher share of PVs compared to the northern cluster, mainly due to the improved weather conditions. In the hydrogen scenario, the yearly investment cost decreases. The increase can be explained by a combination of better utilization of excess renewable electricity and the import of hydrogen from the northern cluster. In the interconnector scenario, the investment cost slightly increases in Central Europe compared to the hydrogen scenario. The reason could be increased capacity of electrolysis, as the cluster is dependent on its production of hydrogen, and hydrogen is not imported from the northern cluster. In the renewable plus scenario, the share of renewable energy increases, and the yearly investment cost drops.

The western cluster has quite similar yearly investment costs and input distribution compared to the central cluster. However, the share of renewable energy services is higher in West Europe. The western cluster has more wet biomass compared to dry. The higher share of wet biomass results in overall lower investment costs compared to the northern cluster. In the hydrogen scenario, the share of renewable energy increases along with the yearly investment costs. The increase in investment might be related to the hydrogen exchange possibility. The western cluster has a scarcity of dry biomass, and thereby syngas. Co-electrolysis units produce additional syngas in other scenarios. In the hydrogen scenario, hydrogen is imported from North Europe and converted into syngas through a reverse water gas shift reactor, which could increase investment costs (Appendix E.18). In the interconnector scenario, the yearly investment cost is increased further due to the increased production in the western cluster. In the renewable plus scenario, the yearly investment cost decreases, as the share of renewable electricity production increases.

The southern cluster is the one with the lowest production and highest capacity imported. Figure 22 reveals the southern cluster to have the lowest investment costs. The cluster has more dry biomass compared to wet, and more solar than wind energy. In the hydrogen scenario, the yearly investment cost spikes for the southern cluster. The increased investment cost is due to the higher production of fuels through the Fischer-Tropsch process. In the base scenario, electricity, and thereby hydrogen, is very scarce, and as a result, fuel production is insufficient. By allowing hydrogen to be imported to the southern cluster, the fuel production increases and thereby the yearly investment cost. Syngas is used for processes creating fuel rather than heat production. In the interconnector scenario, the yearly investment cost decreases, as more electricity can flow into the southern cluster. The need for local and more expensive production capacity decreases. The renewable plus scenario has a high share of renewable electricity producers, and the investment cost decreases.

The southeastern cluster has slightly higher investment costs compared to the southern cluster. The southeastern cluster has more dry biomass than wet biomass and has higher production as it imports to the southern cluster. In the hydrogen scenario, additional hydrogen is imported into the system, allowing the production of transportation fuels to be closer to sufficient. The additional hydrogen results in an increase in invested production capacity for fuel synthesis units and thereby an increase in yearly investment cost. The higher interconnector capacity yields a less rigid system in the southeastern cluster resulting in improved conditions for sector coupling and fuel production. As a result, the investment cost of synthesis plants increases. The renewable plus scenario slightly increase the production of electricity by PVs and wind turbines, which lower the yearly investment cost.

Overall Figure 22 reveals to points of significant interest. First, a high share of dry biomass in a cluster results in a significantly higher investment cost across all scenarios. The reason for the higher investment cost is in coherence with the higher cost of gasifying wood chips versus gasification of wet biomass. Second, investment costs decrease as the share of renewable energy increases. The decrease in investment cost is explained by less need for expensive backup capacity.

6.3 Distribution of Transportation Fuels in 2050

This section investigates the distribution of fuels in the transport sector across the five clusters in the four scenarios. The investigation aims to provide insight into the prioritization of fuels dependent on the system boundaries and the resources available. When investigating the fuel distribution, the base and hydrogen scenarios provide poor results. By interpreting the data extracted from the Sifre model, it reveals the production of jet fuel and is insufficient in these scenarios. The production of jet fuel and methanol is significantly insufficient in the base scenario for all clusters except for the northern cluster. The reason for the insufficient production of jet fuel can be explained by the scarcity of electricity and the general rigidness in the base scenario. The lack of electricity production results in a lack of hydrogen and syngas produced through electrolysis. As Sifre is initially designed to interpret and investigate the electricity system, the demand in electricity sectors is prioritized higher, leading to a lack of supply in the transport sector. The distribution of transportation fuels for the four scenario can be seen in Appendices D.10-D.14. However, this section will focus on the distribution of fuels in the renewable plus scenario, as it shows more satisfactory results compared to the other scenarios.

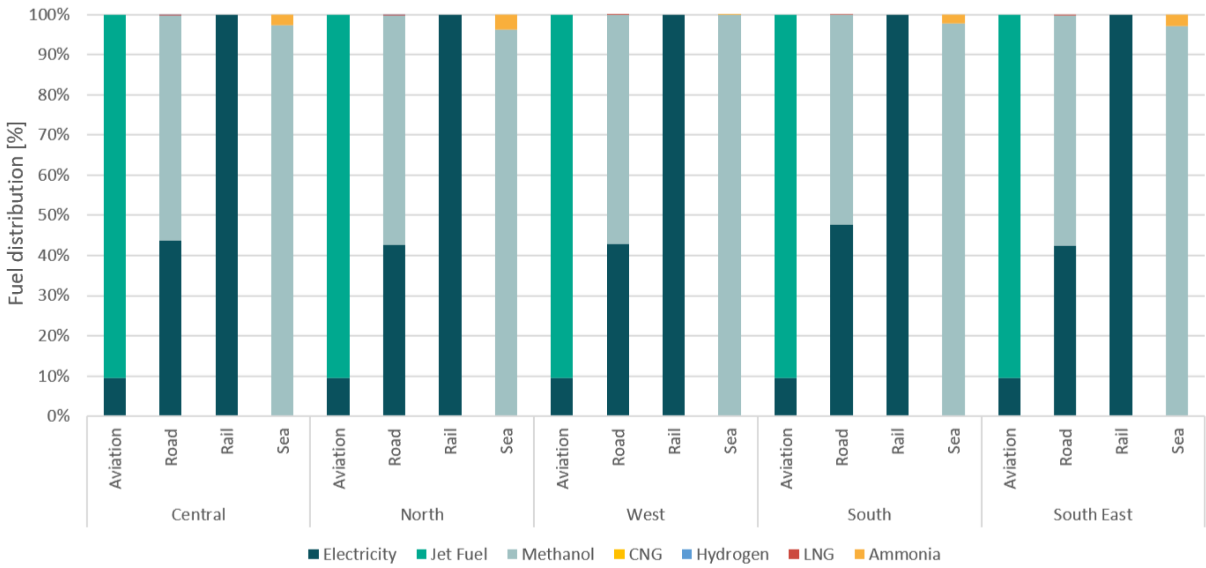

Figure 23: The figure shows the variance in transportation fuel inflow depending on the cluster and transportation mean for the renewable plus scenario. The fuels do have different mechanical efficiency, which must be considered. For figures showing the distribution in the three other scenarios see D.11-D.14.

Generally, the aviation sector uses the maximum allowed electricity input in the cluster. The maximum allowed electricity consumption by airplanes is 5%, the rest is supplied by jet fuel. This pattern is the same throughout the clusters indicating electricity is most lucrative. However, technically the range of electric planes is limited, making the possibility of long-distance traveling impossible[46]. With the development and improvement of the technology, this might be plausible, but not soon and might not by 2050. Electricity covers almost 10% of the mechanical demand for aviation in Figure 23, due to the difference in fuel efficiency between jet fuel and electric engines[47].

Looking at Figure 23, the road transport sector is composed of electricity, methanol, and LNG. The road transport sector can also consume CNG and hydrogen to some extent. However, these are not selected in the renewable plus scenario. Electricity can cover a maximum of 70% of the demand, while methanol can cover a maximum of 100%. The combustion of methanol has a lower mechanical efficiency compared to the electrical engine[47]. As a result, the production of methanol is higher than electricity for the transport sector energy-wise. In Figure 23, it is revealed the road transport mechanical demand is covered by a combination of methanol and electricity along with a minimal share of LNG. The maximum allowed share of electricity is not consumed. However, methanol appears to be produced lucratively in the renewable plus scenario. The production is either a byproduct from the Fischer-Tropsch process or produced by synthesis, where syngas and hydrogen are needed. These are rather expensive. However, they might be produced efficiently in hours with low electricity prices and stored, resulting in significant consumption in the road transportation sector.

The rail sector has the option of unrestricted supply by either electricity or methanol. The rail sector is supplied 100% by electricity, as it appears to be the cheapest option. The rail sector is a rather small sector, with limited demand. The pattern of 100% supply using electricity is the same across all clusters in all scenarios (Appendices D.11-D.14).

The sea sector has the option of being fueled by 20% ammonia, and otherwise unrestricted consumption of methanol or LNG. In the renewable plus scenario, it is evident that the share of methanol is dominant. Ammonia is selected to a small degree. Especially the northern cluster selects ammonia to fuel ships. In the western cluster, it appears ammonia is not a lucrative choice.

6.4 Role of CHP and Boiler Units in a Future Sustainable Energy System

Traditionally gas CHP is used in the electricity sector in hours with peak loads. As intermittent technologies have increased their production in the electricity system, the gas CHP units have become crucial in hours with low production of electricity from wind turbines and photovoltaic cells, where they serve as backup production. When simulating a sustainable energy system, the role of gas CHP units and gas boilers is an essential topic of discussion. Bio CHP and boilers are included in this section to investigate the overall use of biomass resources not utilized in the transport sector. Generally, gas CHPs have some of the highest operating costs in the system. However, the investment in these is quite low, making them ideal as backup capacity[43]. In Sifre, the gas CHP unit is capable of using either methane, hydrogen, or biogas for fuel consumption. The gas boilers enable the use of syngas, hydrogen, or methane as fuel, the same account for the HTPH gas turbines. The bio CHP and boiler uses wood chips.

Figure 24 shows the mix of fuels in different scenarios in the clusters along with the corresponding heat and electricity production from boilers and CHP units. Looking at Figure 24, it is evident that the northern cluster has a higher production of heat and electricity in the hydrogen and base scenarios. These do allow less availability of renewable electricity production or exchange of electricity with surrounding clusters, and therefor more backup is needed. In the renewable plus scenario, the production of heat and electricity from CHP and boiler units is significantly low. The need for backup decreases both in the renewable and interconnector scenario. The base, renewable, and interconnector scenario include wood chips. In the hydrogen scenario, wood chips are gasified, and syngas is converted to hydrogen through water gas shift. Hydrogen can be exchanged to the neighboring cluster. Hydrogen is selected in the base and hydrogen scenario, which are more

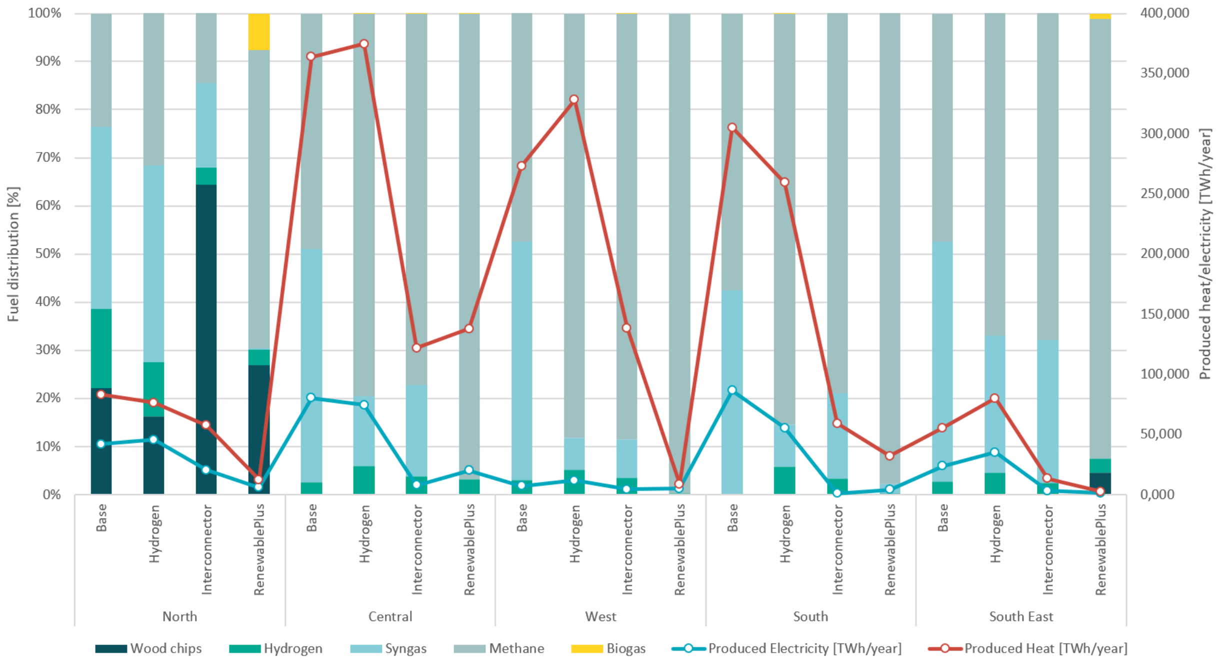

Figure 24: The figure shows the fuel distribution in bio and gas CHPs and boilers across the five clusters in the four scenarios. The secondary axis shows the heat and electricity production.

resource-scarce and rigid compared to the other two scenarios.

In the central cluster, the production of heat and electricity from the boiler and CHP units spikes in the base and hydrogen scenario. The distribution of fuels in the base and hydrogen scenario is quite similar and consist of mainly syngas and methane, along with a smaller share of hydrogen. The need for backup drops in the interconnector scenario and the share of syngas drops too. Methane is imported from the northern cluster and used in the gas CHP and boiler units in West Europe. The production of heat and electricity increases slightly in renewable plus scenario methane is imported from the north and utilized for backup production.

The western cluster has a relatively low production of electricity throughout all simulation scenarios. Gas boilers cover the need for heat in the base, hydrogen, and interconnector scenarios. Electric boilers are used in the renewable scenario. In the base and hydrogen scenarios, syngas and methane are mainly used, along with minor consumption of hydrogen. In the interconnector scenario, the syngas is replaced with methane. Trade of methane between clusters increases in the interconnector scenario, which might make the availability more flexible, resulting in it being prioritized.

In the southern cluster, imported methane serves a crucial role in the backup capacity for electricity production. The production is exceptionally high in the base and hydrogen scenario. The interconnector scenario allows a higher trade capacity of electricity, lowering the production in

CHP units. The heat is produced in electric boilers, lowering the heat production in gas/bio boilers and CHPs. In the renewable plus scenario, the boiler and CHP capacity are low and fueled mainly by imported methane. Syngas is rightfully prioritized in the transport sector for the renewable plus scenario and is not consumed in the gas boiler.

The southeastern cluster shows the same pattern as the other clusters and has the highest production from boilers and CHP units in the base and hydrogen scenario. The production from boilers and CHP units spikes in the hydrogen scenario for the southeastern cluster. Mainly due to the increasing availability of hydrogen in the cluster, which is imported. In the interconnector scenario, the production drops and consists more of methane due to the increased capacity of electricity and methane interconnectors. In the renewable plus scenario, the syngas is not used in the boilers and CHP units, but more so in the transport sector. In the renewable plus scenario, the fuels are a combination of mostly methane, along with smaller shares of hydrogen, wood chips, and biogas.

Looking at the results from Figure 24, it is evident that biogas is only consumed to a noticeable degree in the renewable scenario in the northern and southeastern cluster. Despite biogas being cheaper due to no intermediate process from upgrading to methane, the use of it is low. However, methane has the advantage of being traded between clusters and can be utilized throughout Europe regardless of origin. Sifre does have the ability to model biogas in the gas interconnector lines. However, this would result in problems with a variation of the calorific value and quality of gas in the pipes[48].

6.5 Pattern of Cross-border Trade in Europe

This section will investigate the cross-border trading of electricity and methane, along with hydrogen in the respective scenario. The aim is to locate hot spots in Europe, where resources are more abundant than the local need, along with finding locations in Europe which experience a scarcity of resources. In the case of this thesis, resources include renewable technologies and biomass resources. The resource availability is elaborated in Section 4.2. In Figure 25, a Sankey diagram shows the direction and net capacity traded between clusters.

The results extracted from the Sifre model reveals the southern and central clusters to be the most resource-scarce clusters. When looking at the trade pattern in the base scenario, it is found the electricity mainly originates from the northern, western, and southeastern clusters and transfers to the central and southern clusters. Central has a high demand for electricity both due to population density and a significant industry sector. The same observation transfers to the heat demand. Heat is generated through boiler/CHP units or electric boilers, increasing the need for

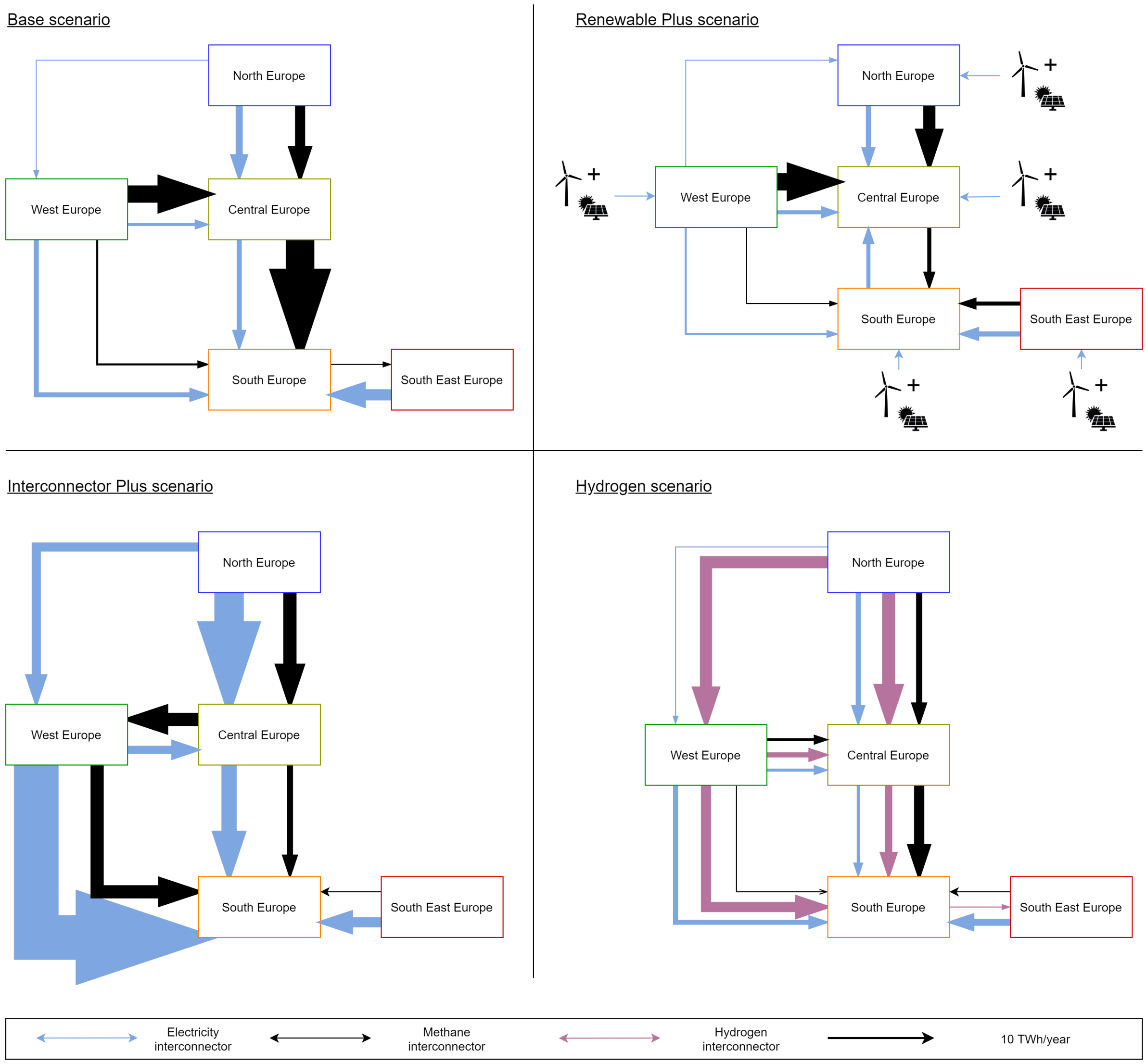

Figure 25: The figure shows a Sankey diagram of the net traded electricity, methane, and hydrogen between clusters in the four simulation scenarios.

either electricity or gas and biomass. The southern has the same problems, however, with lower demand and more scarcity of resources, which results in need of imported resources.

The methane interconnector lines show similar behavior as the electricity lines. A considerable amount of methane is imported to the southern cluster, mostly from Central Europe. However, the central cluster imports methane from North and West Europe. It can, therefore, be assumed the methane in the southern cluster is originally from the northern and western cluster, and restrictions on the methane interconnector between West and South Europe limits trade on the direct route between the two clusters. The methane in the southern cluster is used for heat and electricity production in gas CHP units (Appendix E.4).

The renewable scenario allows more production of renewable electricity within the clusters.

As a result, the southern cluster has increased its dependence significantly. The scarcity of electricity in South Europe decreases substantially, and as a result, electricity flows towards the central cluster instead. The western cluster especially experiences an abundance of resources and, as a consequence, becomes a hot spot for electricity. West Europe exports electricity to all neighboring clusters, which is a slight change from the base scenario, where electricity mainly flows from North to West Europe. The electricity from West Europe is further exported to the central cluster through the north cluster. The same thing happens from the southeastern cluster, where electricity is traded through South Europe to Central Europe. Overall it is evident that the net cross-border trade of electricity has decreased, and clusters are generally more dependent on their production and energy services.

The net trade of methane becomes less across Europe. The need for methane in boilers and CHPs has decreased as a result of more electricity in the clusters. The net trade between the southern and southeastern cluster has shifted, and methane mainly flows from the southeastern to the southern cluster. The quantity of methane has increased in the southeastern cluster as more biogas is upgraded using hydrogen. More biogas is also upgraded with hydrogen in the northern cluster increasing trade between the northern and central cluster. The trade between the western and central cluster remains the same. The central cluster exports less methane to the southern cluster and uses it locally for steam methane reforming creating syngas for the transport sector along with use in gas boilers.

The net trade of electricity increases greatly in the interconnector scenario as the restrictions on trade between clusters are minimized. Looking at Figure 25, it is shown that the northern and western clusters are exporting great quantities of electricity throughout the year to the southern and central clusters. The pattern of net trade between the southern and southeastern cluster remain similar to the base scenario. However the quantities traded between them changes evident from the sankey diagrams in Appendices E.4, E.5, E.14, and E.15. In the interconnector, the electricity capacities traded between them increase. The greatest increase of trade is between the southern a western cluster, revealing the western and northern clusters to be hot spots for electricity production.

The increase in electricity trade lowers the trade of methane between the cluster, as the need for backup using gas CHP units has decreased. The most significant change in the trade of methane in the interconnector occurs between the central and western cluster, as the net trade has shifted direction. The methane from the northern cluster is traded through Central Europe to the western cluster. Central Europe has, in other clusters, used steam methane reforming to produce syngas. However, in the interconnector scenario, the Co-electrolysis unit is used, lowering the need for methane in the cluster (Appendix E.12). The quantity of methane traded between Central and South Europe decreases significantly compared to the base scenario, while the capacity between West and South Europe increases.

In the hydrogen scenario, the new interconnector option provides minimal changes to the electricity system. The trade of electricity is decreased slightly between the central and northern cluster, as the northern cluster uses more electricity for hydrogen production. The net trade between the southern and southeastern clusters decreases. One reason could be the option of using hydrogen in CHP and boiler units in the southern cluster, lowering the need for import of electricity in the cluster.

The net trade of methane decreases significantly throughout Europe with the option of trading hydrogen alongside methane and electricity interconnectors. The use of hydrogen in the boiler and CHP unit increases in the central, western, southern, and southeastern clusters (Appendices E.17-E.20). The increased use of hydrogen lowers the urgency and trade of methane. The decrease of methane traded between the central and southern cluster results in the direction of the net traded methane between the southern and southeastern cluster to switch.

Figure 25 shows North Europe as a hot spot for hydrogen. Hydrogen is exported from North Europe to the central and western cluster and further to the southern and southeastern cluster. As a result, North Europe feeds the entire hydrogen system and only imports a small amount of hydrogen to the system (Appendix E.16). The western cluster does have a small positive net trade and exports more hydrogen than is imported (Appendix E.18). Thereby the western cluster does boost the hydrogen supply across borders to the southern and central clusters. However, the northern does produce more hydrogen. The production of hydrogen in the northern cluster is both through electrolysis and water gas shift. The wood resources are rather high in the northern cluster, and syngas from thermal gasification is used to produce hydrogen through the water gas shift reactor (Appendix E.16).

6.5.1 Market Liquidity

Figure 26 shows the liquidity of the clusters in different scenarios. Liquidity is the total energy traded between cluster divided by the generated electricity within the cluster[31]. Liquidity can be used as a factor to determine the self-reliance of the cluster. In the figure below, the liquidity is divided into import and export between clusters and has been calculated yearly.

From Figure 26, it is evident that the interconnector scenario leaves the cluster more dependent on one another. The southern cluster imports almost 60% of generated electricity from surrounding clusters. The northern cluster exports above 40% of generated electricity to surround-

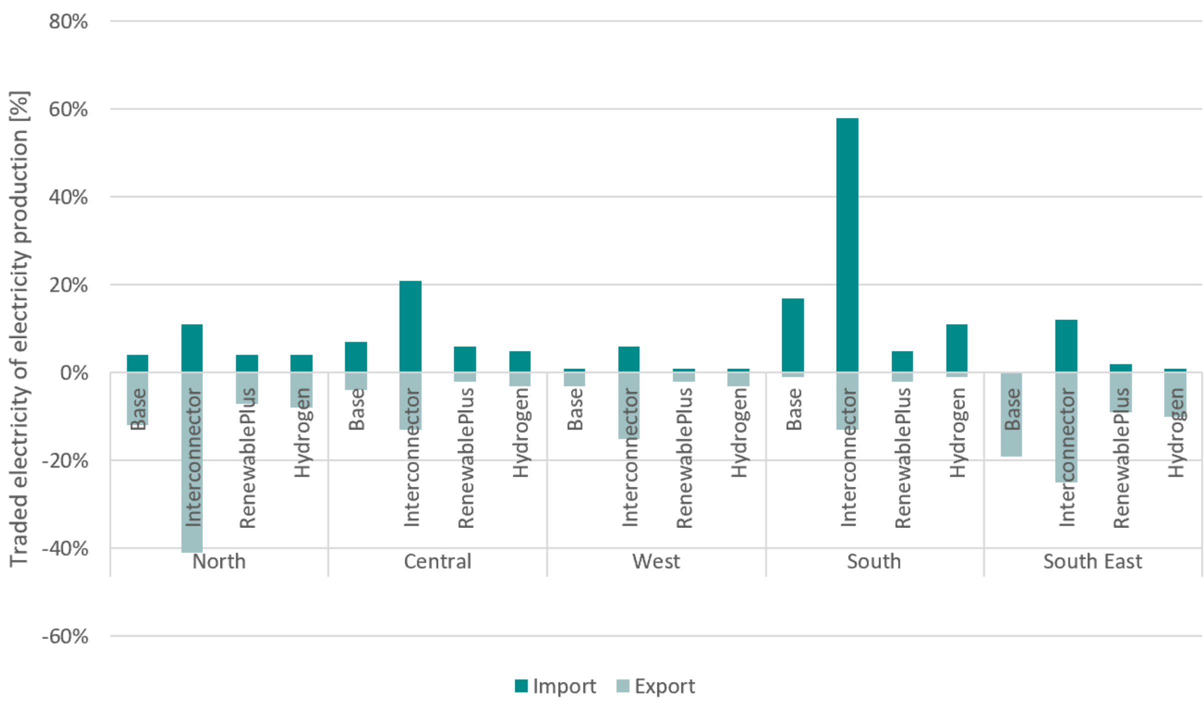

Figure 26: The figure shows the liquidity of the clusters across Europe in the four simulation scenarios is divided into import and export. The figure shows the imported and exported electricity in the clusters in the percentage of locally produced electricity.

ing clusters in the same scenario. The western cluster appears to be the most self-reliant of the clusters where most electricity consumed is produced locally. This pattern does not change despite the scenarios.

The figure shows that the exporting clusters are the northern, western, and southeastern clusters. In the base scenario, the southeastern cluster is significantly self-reliant, with no import from the southern cluster. The electricity trade is a one-way trade from South East Europe to South Europe.

The south and western clusters are the most resource-scarce clusters; as a result, these clusters are importing more than they are exporting. Notably, the southern cluster exports a limited amount of electricity. When comparing the base and hydrogen scenario, the imported capacity does lower. This decrease in imported electricity can be explained by more hydrogen in the clusters, lowering electricity consumption for electrolysis along with having hydrogen for electricity production in CHP units.

6.6 Socio-Economic Evaluation of Simulation Scenarios

This section will sum up the findings of the four simulation scenarios in Sifre and investigate the socio-economic costs in the five clusters. The socio-economic cost will be used as a final evaluation of the four scenarios across the five clusters. The socio-economic calculation includes investments and fixed O&M costs from the ADAPT layer of Sifre along with operation costs, producer, and bottleneck revenues based on data from the simulation results. The simulation results include electricity, methane, and hydrogen prices along with traded capacity between clusters of these and production within the cluster on an hourly basis the summation of these yields the socio-economic cost. For comparison, Figure 27 shows the socio-economic costs per person in the clusters.

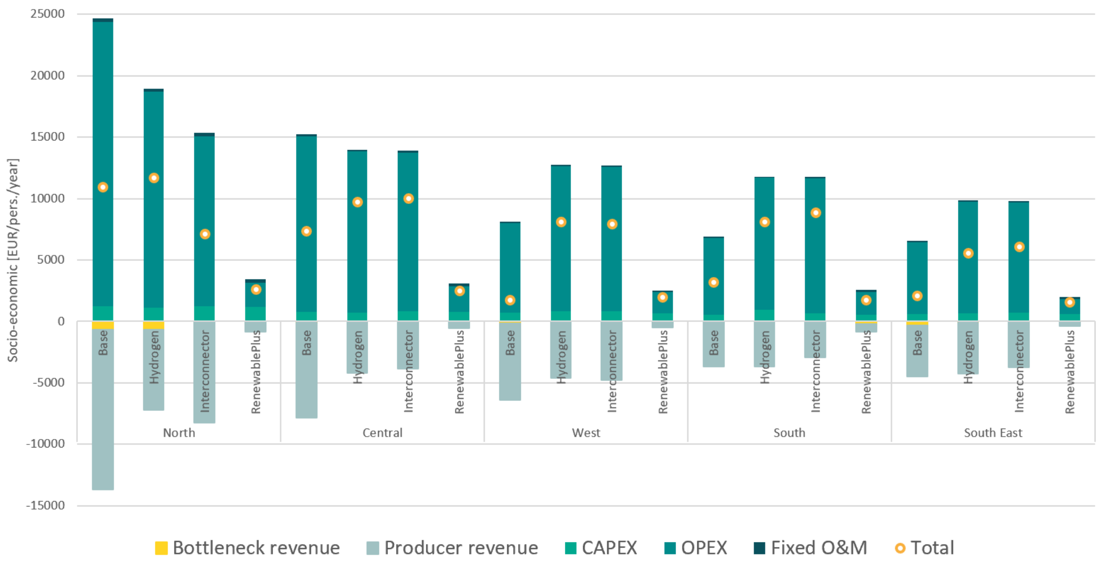

Figure 27: The figure shows the socio-economic within each cluster in the four simulation scenarios. The cost includes yearly investment, fixed O&M, and operation cost along with producer revenues of electricity production and bottleneck revenue of trading electricity, hydrogen, and methane.

Figure 27 reveals the dominating factors in the socio-economic calculation to be the operation costs and producer revenue. In the base, hydrogen, and interconnector scenario, these are higher for the northern cluster compared to the others. The OPEX cost and producer revenue are expected to be high due to the high electricity prices in these scenarios found in Section 6.1. In Section 6.2, it was found that the northern cluster has more dry biomass resources compared to the other clusters. The drying and gasification of dry biomass require higher electricity consumption compared to anaerobic digestion of wet biomass resources (Appendix A). The share of dry biomass explains the higher OPEX in the northern cluster. The substantial production of cheap electricity from wind turbines in the northern cluster combined with a high electricity price gives a high producer revenue. The central, southern, and southeastern clusters also have a high share of dry biomass, increasing the production cost (Figure 22, Section 6.2).

The western cluster has significantly lower costs compared to the northern cluster. Along with being a more population-dense cluster, the western cluster also has a higher share of renewable energy (Figure 21, Section 6.1.5), is more self-reliant, and does not increase production significantly for its size to export methane and electricity to the southern and central clusters.

From Section 6.1, it was found that increasing interconnector capacity or implementing hydrogen interconnectors both have positive implications on the electricity price. In both cases, the electricity price more than halved. These effects are transferred to the socio-economic calculation, where producer revenues are generally decreasing. However, in all cases, except for the northern and central cluster, the OPEX increases. The increase in OPEX explains the increase in the production of fuels for the transport sector, e.g., jet fuel, increase production costs. The increase in the production of fuels is evident from Appendix D.10. The socio-economic investigation does not include the costs of not meeting the fuel demand; however, if it did, the costs in the base scenario would increase. As discussed in Section 6.1, the base system is somewhat rigid, making hydrogen and fuel production difficult. Allowing increasing trade of electricity or hydrogen interconnector improves conditions for meeting the fuel demand across Europe. Generally, the hydrogen and interconnector scenario results in similar OPEX and producer revenue. However, in the northern cluster, the OPEX is higher in the hydrogen scenario due to the significantly increased production of hydrogen.

In the renewable scenario, both the OPEX and producer revenue decreases significantly in all five clusters. The drop can be explained by the substantial decrease in electricity price found in Section 6.1. The production units needing electricity to operate (e.g., electrolysis, heat pumps, and electric boilers) now have significantly lower operating costs. However, lower electricity prices also result in lower production revenue, as the market price of electricity is closer to the operation cost of renewable electricity services. The total socio-economic cost decreases significantly along with the OPEX cost, making the renewable scenario the most socio-economic feasible scenario in all clusters. The socio-economic cost is also rather low in the western, southern, and southeastern cluster. However, the demand for transport fuels is not met. Hence, increasing the renewable capacities throughout Europe is both beneficial in regards to meeting demands and improving the socio-economic cost.

The bottleneck revenues have a slight significance in the socioeconomics of the clusters in the four scenarios. In Figure 27, the implications of bottleneck revenues are only viable in the northern cluster in the base and hydrogen scenario and the southern and southeastern clusters for the renewable and base scenario, respectively. In Appendix D.15, a figure shows the bottleneck revenue across Europe in all four simulation scenarios.

For the northern cluster, bottleneck revenues are highest in the base and hydrogen scenario. In the base scenario, the revenue is due to the trade of electricity with the western and central clusters. The revenues related to the trade of methane are rather low and only account for a few percent of the bottleneck revenue in the base scenario, as the price is quite similar through Europe (Appendix D.1). In the hydrogen scenario, the bottleneck revenue increases slightly, and the revenue is mainly related to the trade of hydrogen. The revenue of trading electricity only accounts for approximately 40% of the total revenues. In Figure 27, it is revealed that the socioeconomics of the hydrogen scenario increases in the northern cluster compared to the base scenario. The increase shows the bottleneck revenues are not sufficient to make the hydrogen scenario socio-economically feasible. In the interconnector, scenario prices are somewhat similar throughout Europe, making the bottleneck revenues low. In the renewable scenario, the bottleneck revenue decreases further as prices are significantly lower in this scenario.

In the central cluster, the bottleneck revenues are significantly lower compared to the northern cluster in all simulation scenarios. The revenues are highest in the base scenario, mainly due to the trade of electricity. In the hydrogen scenario, the central cluster does also benefit from trading hydrogen to the southern cluster. The trade of hydrogen accounts for approximately 25% of the bottleneck revenue. The bottleneck revenues are significantly lower in the interconnector and renewable scenario. The trade of methane is responsible for nearly 20% of the revenues in the interconnector scenario.

The western cluster is found to be the most self-reliant cluster in Section 6.5.1. As a result, the bottleneck revenues are rather low in the western cluster, when accounting for the size of the cluster. The highest bottleneck revenues are in the base scenario and are almost exclusively from the trade of electricity to neighboring clusters. The bottleneck revenues are lower in the hydrogen scenario. From Appendix D.15, it is evident that the trade of hydrogen accounts for around 30% of the revenue in the hydrogen scenario. In the interconnector and renewable scenario, the bottleneck revenues are low and mainly from the trade of electricity.

In the southern cluster, the bottleneck revenue is highest in the renewable scenario. The trade of electricity causes revenue in the central cluster. From Figure 18 in Section 6.1, it is evident there is a significant gap between the electricity price in the southern cluster and the central cluster, generating substantial revenue in the southern cluster. In the three other scenarios, bottleneck revenues are rather low in the southern cluster and mainly related to the trade of electricity. In the interconnector scenario, nearly. 35% of the revenues are related to the trade of methane.

The southeastern cluster has the highest bottleneck revenues in the base scenario. The revenue is mainly related to the trade of electricity, and methane only accounts for around 2-3% of the revenue. In the hydrogen scenario, the revenue of trading hydrogen accounts for less than 10% of the total revenue. Revenue from trading hydrogen indicates some trade of hydrogen from South East Europe to South Europe. In the interconnector and renewable scenario, bottleneck revenues are low. In the renewable scenario, trade of methane accounts for above 60% of the revenue. Methane is traded to the southern cluster and used in the steam methane reforming process to produce hydrogen and syngas (Appendix E.9).

7 Concluding Remarks

As the thesis comes to an end, several remarks are worth mentioning. First, a presentation of the most significant findings is compiled in a small summary. Afterward, a small discussion of issues not included is conducted to recommend further topics for investigation. The thesis has investigated a sustainable European energy system to locate scarcities and resource strengths across Europe. Further, solutions to equalize resources are conducted. All analyses have been done using a macro-level holistic approach. Therefore conclusions derived from this thesis serve as initial conclusions and will need further investigation to ensure are more accurate analysis of resource movements through Europe.

7.1 Summary

For simplicity reasons, Europe is divided into five clusters in this thesis. A base scenario of the energy system within each of the clusters has been modeled. Restrictions on renewable capacity, biomass resources, and interconnector capacity are included in the base scenario. After the simulation of the base scenario, several suggestions for alterations to the system were made. The adjustments done aimed to lower electricity prices along with meeting demands in the clusters. In total, three suggestions to improve the base model have been investigated in this thesis. The first adjustment was to increase the renewable capacity in the clusters. The second scenario increased interconnector capacity significantly. In the third scenario, the possibility of trading hydrogen between clusters was included.

Throughout the simulation scenarios, it was evident that the Northern and Western clusters were generally the most resource stable clusters. Likewise, the central and southern clusters proved to be more dependent on importing resources from surrounding clusters due to resource scarcity. The South Eastern cluster proved to be more resource secure. Evident from the energy flowing mostly from South East Europe to South Europe. In the base, hydrogen, and interconnector scenario, the southern cluster has been the node, to which most resources flowed. However, when increasing the renewable capacity, the energy mainly flows towards the central cluster.

Increasing the renewable capacity across Europe was found to be the most socio-economic beneficial, and leading technology solution. Higher availability of electricity from solar and wind resources yielded a more flexible system. Hydrogen production from electrolysis units was carried out more lucratively as the electricity prices were significantly lower in this scenario. The lower electricity prices improved conditions for sector coupling.

The hydrogen scenario revealed North Europe to be a hot spot for hydrogen, and the resources were transferred across all of Europe. However, the socio-economics of this scenario did not improve compared to the base scenario. The same was evident in the interconnector scenario, where the socio-economic calculation showed an increase.

The last remark is related to the role of backup electricity producers. As the energy system becomes more dependent on renewable energy services, the need for backup in irregular hours becomes more crucial. However, with the increase in capacity on renewable energy services or interconnector, the need for backup lowers. The increased availability of electricity can explain the decrease in these hours.

7.2 Future Work and Recommendations

Throughout the thesis, several findings have been made, which would require further analysis. Several topics of discussion and analysis were not included in the thesis. These discussion points, analysis topics, and other recommendations and presented shortly in this section.

First is the analysis of the consequences of adjusting biomass resources along with implementing more trading possibilities across Europe. Analyzing the consequence of adjusting the availability of biomass resources would be of interest for several reasons. One reason is analyzing the trade of using Co-electrolysis versus having more biomass available for syngas production through thermal gasification and steam methane reforming. Another reason would be the role of CHP and boiler units as more biomass is available. Allowing trade of dry biomass between clusters could also be of interest. Allowing dry biomass to be traded across Europe could reduce the scarcity of syngas and, as a result, secure sufficient fuel resources. Dry biomass could be traded either before the gasification on trains, trucks, or post gasification as syngas in pipes.

Secondly, the current Sifre model does not allow shifting electricity demand. Neither is electric vehicles used for storage during peak hours. Including these in the analysis could allow for a more flexible energy system and higher utilization of renewable electricity produced.

Third, is the trade with countries, not members of ENTSO-E/G. Currently, these are not included. Allowing trade with countries east and south of the European clusters could provide a more flexible system with lower electricity and gas prices, as the availability of these are expected to increase.

Lastly, the sensitivity of technological specifications on production units, along with their costs are worth investigating. Many of the technologies applied in the thesis are not fully commercialized. Hence technological enhancement is expected. Enhancement can both affect the efficiencies and costs of production. Technological enhancement might also result in a higher degree of electrification in the transport sector. With a higher share of electricity in the transport sector, socio-economics are expected to improve.

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A Appendices: Technology processes and costs overview

This appendix serves the purpose of giving a more detailed description of the fuel pathways used in the thesis. The appendix will present each process used in the simulation of the energy system. Information regarding energy balances is also in this appendix, which is used for modeling in the Sifre tool. Sifre operates with energy flows, and the flow diagrams in this appendix are all showing the energy balance of the processes. The cost of the processes is also included, which is used as an optimization input in the ADAPT layer in Sifre. The table containing costs for all processes, storage, interconnectors, and renewable energy production units can be found at the end of this appendix in Appendix A.18.

A.1 Heat areas

Due to the setup of Sifre, heat flows are not specified with mass, pressure, and temperature. To compensate for this, the heat flows have been divided into three areas[2].

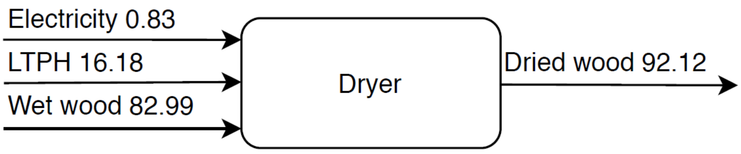
- District heating (DH): District heating has a range from 50°C - 110°C.
- Low-temperature process heat (LTPH): Low-temperature process heat has a range from 110°C - 300°C.
- High-temperature process heat (HTPH): High-temperature process heat has a range from 300°C - 1000°C.

These three areas are used for the processes and areas in Sifre for the simulations concerning this thesis.

A.2 Dryer unit

The dryer unit serves the purpose of drying wood from having a 50% water content to a maximum of 15% water content. The drying process is necessary to prepare the wood for the gasifier process. The wet wood is dried in an evaporation process using LTPH to heat the process. Electricity is input for pump work. The energy balance can be seen below in Figure 28.

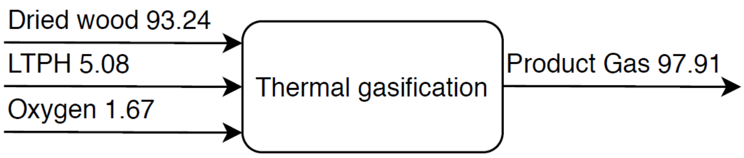
Figure 28: Appendix A: Energy Balance of Dryer Unit [2]



A.3 Thermal Gasification

The thermal gasification unit produces product-gas using mainly dried wood, and process heat along with oxygen as secondary resources. The woody biomass resource is pressurized at 25 bar by process steam, and oxygen is supplied at 25 bar pressure and temperature of 230°C. The steam used in the thermal gasification can be extracted from the low-temperature process heat area. The ratio between oxygen and LTPH is approximately 1:1 on mass [2]. The temperature in the biomass reactor increases, and product-gas is produced at around 890°C. Figure 29 shows the energy balance of the thermal gasification unit.

Figure 29: Appendix A: Energy balance of Thermal Gasification [2]



After the production of product-gas, the gas is cleaned to obtain syngas. Tar compounds such as naphthalene, light hydrocarbons e.g., propane and ethane along with acetylene and ethylene are found in product-gas from the thermal gasification process and are primarily reformed to Hydrogen and Carbon monoxide by catalytic cracking[2]. Figure 30 shows the process of product-gas cleaning. The process contains several sub-processes, which are not described in this thesis. Electricity is consumed in the sub-processes of tar reformation and CO_2-removal. Oxygen is added in the sub-process of ATR catalytic reformation.

Figure 30: Appendix A: Energy balance of product-gas Cleaning [2]

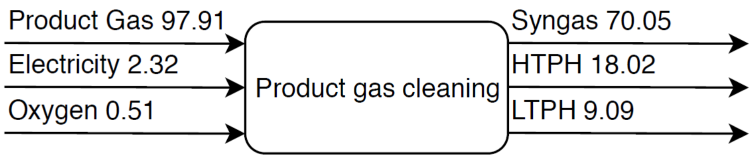
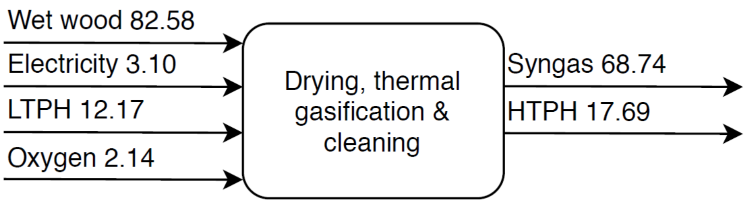


Figure 31 shows the combination of the dryer, thermal gasification, and product-gas cleaning.

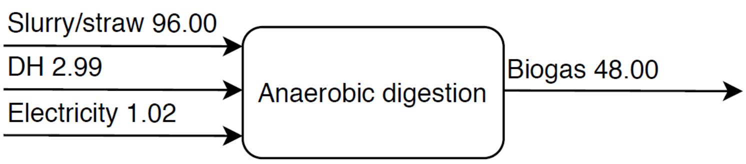
Figure 31: Appendix A: Energy balance of Drying, Thermal Gasification and Cleaning [2]



A.4 Anaerobic Digestion

Anaerobic digestion is used to produce biogas using a mix of straw and manure/slurry in combination with a low-temperature heat source and electricity. In this thesis, manure can be replaced with low-cost sludge resources, which does have a lower efficiency compared to manure. Organic waste can also be applied in the anaerobic digestion[16][18]. The anaerobic digestion process occurs in a digester tank, where the biomass resources are heated to 35-40 °C, which fits with the district heating temperature span. The biomass product consist of 50-70% CH_4 and 30-50% CO_2. Digestion efficiency varies greatly between 20-70%. A low digestion efficiency could indicate the waste sludge feed may not be completely digested. Pretreatment technologies can be used to breakdown the cell wall structure and improve digestion efficiency [18]. Figure 32 shows the energy balance of anaerobic digestion.

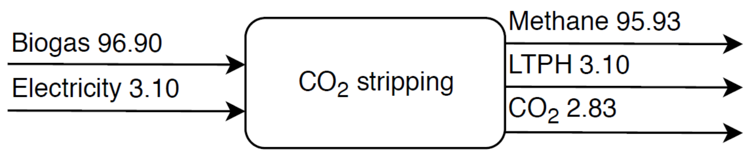
Figure 32: Appendix A: Energy balance of Anaerobic Digestion [18]



A.5 CO_2 Stripping

Before the biogas is injected in the gas grid and utilized for heating or transportation purposes, it must be upgraded. An upgrade of biogas to methane can either be through hydrogenation or CO_2-stripping. In the process of CO_2-stripping the biogas is upgraded by removing the CO_2, and thereby increasing the heating value. The upgrade is done to meet the requirements for gas injected to the natural gas grid, which requires the content of the gas to consist of a minimum of 98,5% methane. The upgrading also consists of removing H_2S, Nitrogen, and ammonia from the gas, depending on the inputs in the anaerobic digestion process. This is, however, neglected in this thesis for simplification reasons[36]. The CO_2-stripping occurs in a scrubber or through pressure swing absorption, PSA. In this thesis, the CO_2-stripping is assumed to be done in a water scrubber. The biogas is injected in a tank where water is added by spray or bubbling. The CO_2 and other gases are more likely to react with the water compared to methane, which is then sorted to the top of the tank and captured for the gas grid. The pressure of the water scrubbing process occurs at a pressure similar to the pressure of the gas distribution inlet net (4-7 bar), and no further pressure is needed before the methane is fed to the gas net[36]. The energy balance of the process is shown in Figure 33.

Figure 33: Appendix A: Energy balance of CO_2 Stripping [36]



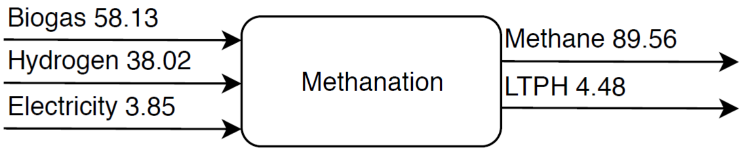
A.6 Methanation

Post the anaerobic digestion, the biogas can be either stripped for CO_2 or the CO_2 gases can be converted to methane by adding hydrogen to the process. Adding hydrogen to the biogas enriches the methane content of the biogas. The CO_2 gasses are converted to methane by the chemical process shown in Equation 1 below[49].

$$CO_2 + 4H_2 \longleftrightarrow CH_4 + 2H_2O \quad \Delta H_{298} = -165 kJ/mol \tag{1}$$

The process of converting the CO_2 gasses into methane requires hydrogen and an electricity source. The process occurs at a temperature equal to the span of the LTPH. The process is catalytic, and most commonly, nickel is used as a catalyst[49][37]. The energy balance of the process is shown in Figure 34.

Figure 34: Appendix A: Energy balance of Methanation [37]

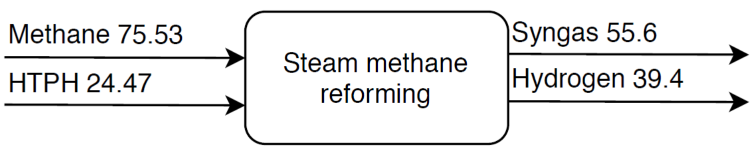


A.7 Steam Methane Reforming

The Steam Methane Reforming is a process, where methane is reformed to syngas and hydrogen at high temperature. High-temperature process heat is applied, as the process occurs at temperatures around 800-900 °C[50]. As a rule of thumb, the efficiency of the Steam Methane Reforming process increases with increasing temperatures. At 900 °C the conversion of methane is almost 100%. The energy balance is shown in Figure 35, and the reaction is shown in Equation 2.

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2 \quad \Delta H_{298} = +206 kJ/mol \tag{2}$$

Figure 35: Appendix A: Energy balance of Steam Methane Reforming [50]



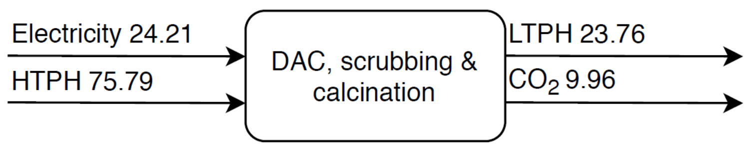
A.8 Direct Air Capture

For the production of electrofuels a carbon source is required, commonly the source is biomass, through thermal gasification or anaerobic digestion. However, in a shortage of biomass, carbon from the atmosphere can be filtered from atmospheric air and applied in the process of generating electrofuels, the process is called direct air capture, DAC. In this thesis, two methods for DAC are investigated the Scrubbing and Calcination method and the Temperature Swing Absorption.

Scrubbing and Calcination

The scrubbing process entails blowing atmospheric air through a scrubbing tower, where CO_2 reacts with a scrubbing agent[40]. The scrubbing agent can either be a sodium - or calcium hydroxide solution. For this thesis, the sodium solution is applied. The process occurs at a temperature of approximately 800 °C at 80 bars of pressure. Some of the heat can be restored in the process, but most are lost to the ambient air being funneled through the scrubber. The process for DAC by scrubbing and calcination requires heat and an electricity source and yields CO_2 as the main product and LTPH as a byproduct[40]. The process is shown in Figure 36.

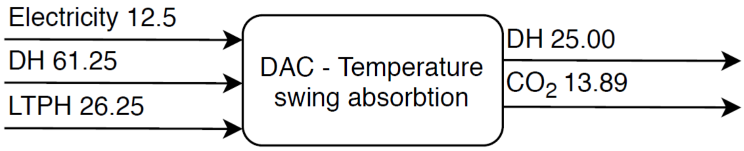
Figure 36: Appendix A: Energy balance of DAC - Scrubbing and Calcination [40]



Temperature Swing Absorption

The second DAC technology is Temperature Swing Absorption, developed by the Swiss company Climeworks. DAC using temperature swing absorption operates a lower temperature compared to the scrubber and calcination process but is, however, more expensive compared to the scrubber (Appendix A.18). In the temperature swing absorption technology CO_2 is filtered from the atmospheric air. First, the air is blown through, and the CO_2 is captured in a filter, whilst the air passes through. Second, the flow of air is stopped, and the filter is heated to approximately 100 ∘C to release the CO_2, which is directed to a tank. Figure 37 shows the energy balance of DAC by temperature swing absorption.

Figure 37: Appendix A: Energy balance of DAC - Temperature Swing Absorption [41]



A.9 Electrolysis

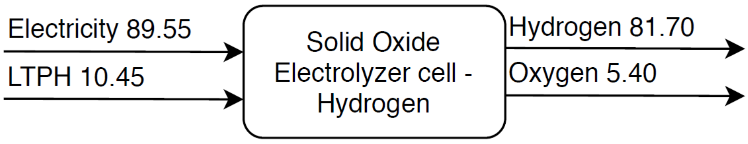
Electrolysis is a process where electricity is used to divide the molecular structure of either water or CO_2 in the case of this thesis. Power is used to create a voltaic difference in the steam (and CO_2) and divide the atoms by the charge of the atoms. Steam is used instead of water to reduce the consumption of electricity. This method is applied in the Solid Oxide Electrolyzer Cell, where a constant heat supply ensures limited reheating of the electrolysis process[43].

Solid Oxide Electrolysis cell - Hydrogen

Through an electrochemical process, an electricity source is used to split steam into oxygen and hydrogen. Hydrogen is attracted to the negatively charged cathode, and oxygen is attracted to the positively charged anode[43]. The chemical reaction is shown in Equation 3, and the energy balance is shown in Figure 38.

$$2H_2O \longrightarrow 2H_2 + O_2 \tag{3}$$

Figure 38: Appendix A: Energy balance of Solid Oxide Electrolysis cell - Hydrogen [43]

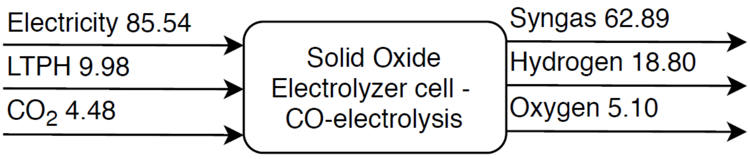


Solid Oxide Electrolysis cell - CO-electrolysis

A CO-electrolysis produces Syngas and Hydrogen in a combined electrochemical process. Carbon monoxide and hydrogen are attracted to the cathode, and oxygen is attracted to the anode[43]. The chemical reaction is shown in Equation 4, and the energy balance is shown in Figure 39.

$$2CO_2 + 4H_2O \longrightarrow 2CO + 4H_2 + 3O_2 \tag{4}$$

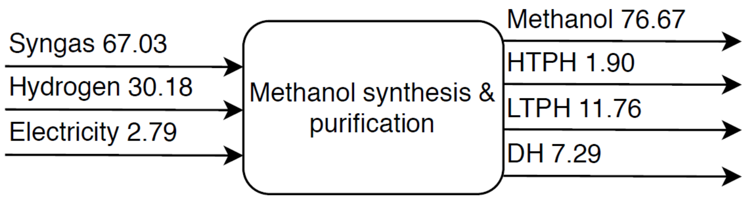
Figure 39: Appendix A: Energy balance of Solid Oxide Electrolysis cell - CO-electrolysis [43]



A.10 Methanol Synthesis and Purification

Methanol Synthesis and Purification is a process used to produce methanol using Syngas, Hydrogen, and Electricity as input. The technology is well established and has been used for fuel production in over 90 years. Formerly coal has been applied. However, in this thesis, syngas and hydrogen are applied. Syngas is compressed to 90 bars, and as a result, a significant power supply is needed[2]. Figure 40 shows the energy balance. It reveals a considerable amount of residual heat from the process, which in Sifre is modeled as a heat splitter, where the heat is supplied to the belonging heat areas.

Figure 40: Appendix A: Energy balance of Methanol Synthesis and Purification [2]

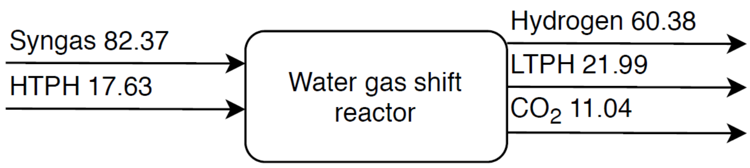


A.11 Water Gas Shift Reactor

The water shift reactor is a process where hydrogen is produced in a high-temperature process. In this thesis, hydrogen production is either done using electrolysis, steam methane reforming, or water gas shift reactor. In hours with high electricity prices, the water gas shift reactor might be more preferable[2]. The reaction in the water gas shift reactor is shown in Equation 5, and the energy balance is shown in Figure 41.

$$CO + H_2O \longrightarrow H_2 + CO_2 \quad \Delta H_{298} = -41,4 kJ/mol \tag{5}$$

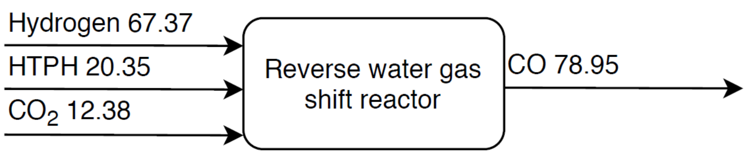
Figure 41: Appendix A: Energy balance of Water Gas Shift Reactor [2]



A.12 Reverse Water Gas Shift Reactor

Reverse water gas shift reactor is used to produce syngas from surplus hydrogen. Reverse water gas shift reactor uses CO_2 and hydrogen as input in a high-temperature process. The process occurs at 750 °C. The HTPH is assumed to be reused internally in the process lower the HTPH demand. The energy balance can be seen in Figure 42.

Figure 42: Appendix A: Energy balance of Reverse Water Gas Shift Reactor [42]



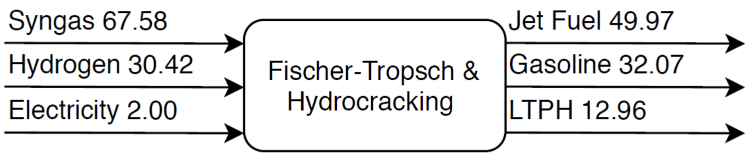
A.13 Fischer Tropsch Synthesis and Hydrocracking

Fischer Tropsch is an industrial process, which has been known for 60 years. The process converts Syngas and Hydrogen into Hydrocarbons. Syngas is produced from either coal, natural gas, biomass resources, or electrolysis. In the case of this thesis, the syngas is produced from biomass resources or electrolysis through direct air capture. The process uses electricity along with hydrogen and syngas as an input. The process of hydrocarbons is shown in Equation 6.

$$nCO + (2n+1)H_2 \longrightarrow C_nH_{2n+2} + nH_2O \tag{6}$$

Fuels used by airplanes are most often kerosene. However, hydrocarbons with between eight and sixteen carbon atoms are all applied in the aviation sector[51]. In the Fischer Tropsch process, there is a distribution of the number of carbon atoms in the output. As a result, the process also produces methanol. Figure 43 shows the energy balance of the Fischer Tropsch process.

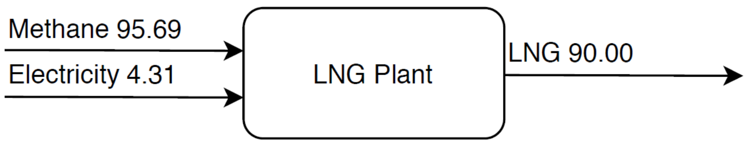
Figure 43: Appendix A: Energy balance of Fischer Tropsch Synthesis and Hydrocracking [51]



A.14 Liquid Natural Gas Plant

Liquid Natural Gas, LNG, is applied as fuel in trucks. The process plant uses methane as input and cools the gas to -162 °C at atmospheric pressure to liquefy the gas. The electricity input is varying with a spread from 1,9 to 3 MJ/kg LNG. In the thesis 2,5 MJ/kg LNG is applied. LNG is required to stay cooled when stored to ensure it does not evaporate. Losses related to the process of cooling methane to LNG is assumed by 10% due to evaporation[38]. Figure 44 shows the energy balance used in Sifre for an LNG plant.

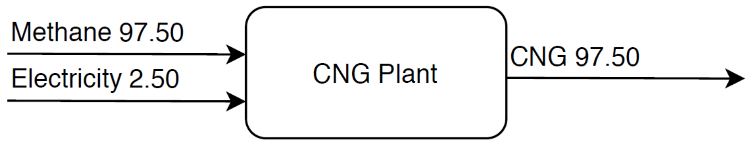
Figure 44: Appendix A: Energy balance of Liquid Natural Gas Plant [38]



A.15 Compressed Natural Gas Plant

Compressed natural gas, CNG, is applied worldwide today and is a well-known technology used to fuel road transport. Electricity is used to compress methane to the pressure between 200-300 bars[39]. The energy balance is shown in Figure 45.

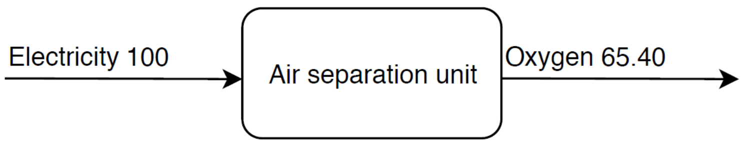
Figure 45: Appendix A: Energy balance of Compressed Natural Gas Plant [39]



A.16 Air Seperation Unit

The air separation unit produces oxygen from atmospheric air using electricity. The unit is used in case the oxygen produced from electrolysis is not sufficient from the thermal gasification process. Figure 46 shows the energy balance of the air separation unit.

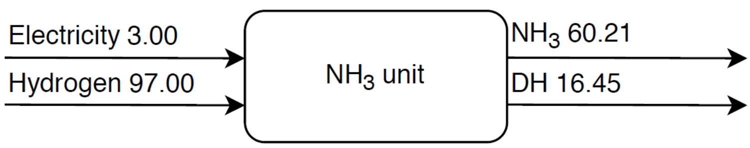
Figure 46: Appendix A: Energy balance of Air Seperation Unit [2]



A.17 Ammonia Production Unit

The ammonia production unit uses hydrogen to produce ammonia. The ammonia production plant is included to produce fuel for sea transport. Nitrogen is included, as the availability of carbon resources might be limited in the future. The process uses atmospheric air in combination with hydrogen to produce ammonia[44]. The process results in some surplus heat, which is supplied to the district heating area in Sifre. Figure 47 shown the energy balance of the ammonia production unit.

Figure 47: Appendix A: Energy balance of Ammonia Production Unit[44]



A.18 ADAPT Investment data

The table below contains the data inserted in the ADAPT investment optimization layer in Sifre. The table only contains the production units where optimization on capacities achieved. Production units for fuel splitting and combustion of fuels are not included as they are only developed due to technical restrictions in the Sifre tool. Storage units for fuels (e.g., wood chips and straw) are not included either and are only included in Sifre to make the consumption of these more flexible.

Table 3: Appendix A: Input in the ADAPT Investment Layer in the Sifre Tool[43][30]

Storage	**Maginal Investment [Mio. EUR/MWh]**	**Fixed O&M [EUR/MW/year]**	**Interest Rate [Pct. p.a.]**	**Lifespan [Year]**
Ammonia	0,00067	0	4	20
Battery	0,1008	0	4	12
Biogas	0,00067	0	4	20
District Heating	0,0023	0	4	30
Hydrogen	0,0033	0	4	30
Oxygen	0,38172	0	4	25
Syngas	0,08	0	4	30
Heat Pump	**Maginal Investment [Mio. EUR/MW]**	**Fixed O&M [EUR/MW/year]**	**Interest Rate [Pct. p.a.]**	**Lifespan [Year]**
Large Heat Pump	0,53	2000	4	25
Interconnectors	**Maginal Investment [Mio. EUR/MW]**	**Fixed O&M [EUR/MW/year]**	**Interest Rate [Pct. p.a.]**	**Lifespan [Year]**
Electric	NA	NA	NA	NA
Gas	0,126	0,005	4	50
Hydrogen	0,173	0,007	4	50
Production Units	**Maginal Investment [Mio. EUR/MW]**	**Fixed O&M [EUR/MW/year]**	**Interest Rate [Pct. p.a.]**	**Lifespan [Year]**
Air seperation	2,147	64447	4	20
Ammonia synthesis	0,12	2400	4	20
Anaerobic digestion	0,372	26009	4	20
CNG compression	0,152	3046	4	20
CO2 stripping	0,246	6711	4	20
Co-electrolysis	0,565	14903	4	20
DAC - scrubbing	0,826	15944	4	20
DAC - TSA	0,638	16527	4	20
Electric boiler - HTPH	0,06	920	4	20

Electrolysis - hydrogen	0,591	14754	4	20
FT synthesis	0,505	9857	4	20
Gas boiler	0,05	1700	4	20
Gas CHP NG	0,52	18000	4	20
Gas CHP NG/BG	0,52	18000	4	20
Gas turbine HTPH	0,52	18000	4	20
HydroProduction	1,8	0	4	50
LNG plant	0,265	5306	4	20
Methanation	0,12	2400	4	20
Methanol synthesis	0,177	5317	4	20
RWGS	0,064	3086	4	20
Steam methane reforming	0,283	5654	4	20
Steam turbine	0,483	14476	4	20
Thermal gasification	0,647	25885	4	20
Water shift	0,073	3518	4	20
Wood chips boiler	2,621	41028	4	20
Wood chips CHP	0,8	16000	4	20
Renewable units	**Maginal Investment [Mio. EUR/MW]**	**Fixed O&M [EUR/MW/year]**	**Interest Rate [Pct. p.a.]**	**Lifespan [Year]**
Onshore Wind	0,83	21200	4	30
Offshore Wind	1,71	32100	4	30
Solar	0,85	8500	4	40

B Appendices: Energy demands and resource constraints in the five clusters

B.1 Electricity Demand - Sifre Input

Table 4: Appendix B: Sifre Input - Electricity demand [11]

Cluster	**Area**	**Total [MWh/y]**
North	Industry	103.404.527
North	Classic	1.331.668
Central	Industry	200.086.446
Central	Classic	4.880.734
West	Industry	336.218.836
West	Classic	7.154.128
South	Industry	128.185.266
South	Classic	5.436.002
South East	Industry	51.416.516
South East	Classic	575.642

B.2 Heat Demand - Sifre Input

Table 5: Appendix B: Sifre Input - Heat demand [11]

Cluster	**Area**	**Total [MWh/y]**
North	DH	133.398.146
North	LTPH	45.372.075
North	HTPH	28.648.728
Central	DH	629.390.973
Central	LTPH	291.109.147
Central	HTPH	187.327.953
West	DH	883.463.698
West	LTPH	383.242.882
West	HTPH	250.625.137
South	DH	426.878.275
South	LTPH	168.828.735
South	HTPH	108.654.354
South East	DH	75.837.713
South East	LTPH	44.258.410
South East	HTPH	28.968.232

B.3 Transport Demand - Sifre Input

Table 6: Appendix B: Sifre Input - Transportation demand [11]

Cluster	**Type**	**Total [MWh/y]**
North	Aviation	28.504.423,77
North	Road	30.498.005,68
North	Sea	4.523.185,61
North	Rail	689.653,79
Central	Aviation	99.328.937,29
Central	Road	107.055.893,66
Central	Sea	16.182.562,37
Central	Rail	2.451.859,05
West	Aviation	170.042.435,16
West	Road	180.059.471,66
West	Sea	26.881.521,27
West	Rail	3.944.829,88
South	Aviation	62.861.453,67
South	Road	71.028.920,49
South	Sea	10.757.341,39
South	Rail	2.007.760,08
South East	Aviation	23.879.928,22
South East	Road	25.249.315,41
South East	Sea	3.899.602,63
South East	Rail	475.258,41

B.4 Countries included in Alterra Biomass Study

Figure 48: Appendix B: Overview of countries included in Alterra Study concerning biomass availability[16]

B.5 Simplification of Biomass types from Alterra Study

Table 7: Appendix B: Fuel types in the Alterra Biomass study along with simplifications of these for application in the thesis[16].

Biomass type	**Source**
Wood	Additional harvestable round wood
	Landscape care wood
	Other industrial wood residues
	Paper cardboard
	Perennials: Woody
	Post consumer wood
	Primary forestry residues
	Prunnings
	Roundwood
	Sawdust
	Sawmill by-products
Sludge	Black liquor
	Common sludges
Organic Waste	Animal waste
	Municipal Solid Waste (Not landfill, composting, recycling)
Manure	Manure
Straw	Grass cuttings abandoned grassland
	Perenials: Grassy
	Straw
	Verge gras
Not used in Thesis	Cereals
	Forrage maize
	Maize/corn
	Municipal Solid Waste (Landfilled, composted, recycled)
	Rape
	Sugarbeet
	Sunflower
	Used fats and oils

B.6 Modelling of Hydro Plant in Sifre

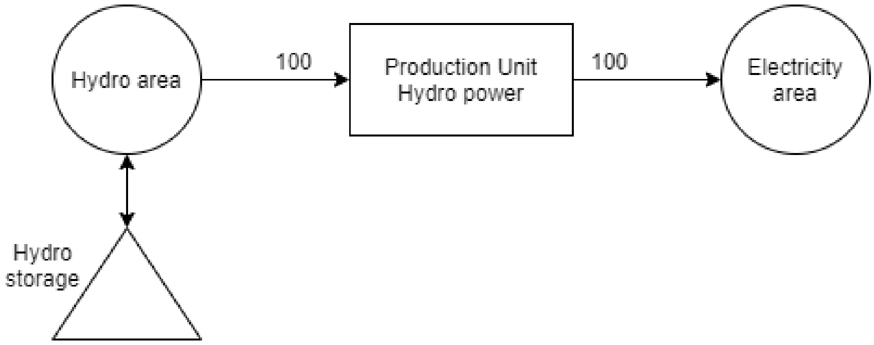


Figure 49: Appendix B: Modelling of Hydro Plants in Sifre

B.7 Potential of Renewable Energy Sources based on TYNDP20 study

Table 8: Appendix C: Potential of Renewable Energy Sources based on TYNDP20 study[12]

Country	**Onshore wind potential [MW]**	**Offshore wind potential [MW]**	**Solar potential [MW]**	**Hydro potential [MW]**
Albania	3200		1800	2900
Austria	13000		22000	15000
Belgium	7100	6200	19000	1500
Bosnia and Herzegovina	3100		3200	2300
Bulgaria	6300		13000	3400
Croatia	3800		5400	3400
Czech Republic	13000		15000	2300
Denmark	6300	13000	5700	0
Estonia	3300		840	0
Finland	22000		3300	3200
France	78000		79000	26000
Germany	110000	24000	140000	15000
Greece	16000		18000	4600
Hungary	2500		16000	57
Ireland	9400		3700	530
Italy	24000		71000	27000
Latvia	1700		1500	1600
Lithuania	3800		2600	1300
Luxembourg	450		470	1400
Montenegro	1200		790	1300
Netherlands	19000	17000	25000	47
Norway	10000		2000	36000
Poland	17000		24000	2200
Portugal	13000		15000	9200
Republic of North Macedonia	500		2100	1200
Romania	8000		6500	6800
Serbia	6900		7700	3900
Slovak Republic	1000		2700	2500

Slovenia	1000		5100	1900
Spain	61000		86000	24000
Sweden	31000		9100	17000
Switzerland	1900		13000	16000
United Kingdom	32000	37000	38000	6000

C Appendices: Modeling set-up and assumptions

C.1 Overall Model Set-up in Sifre

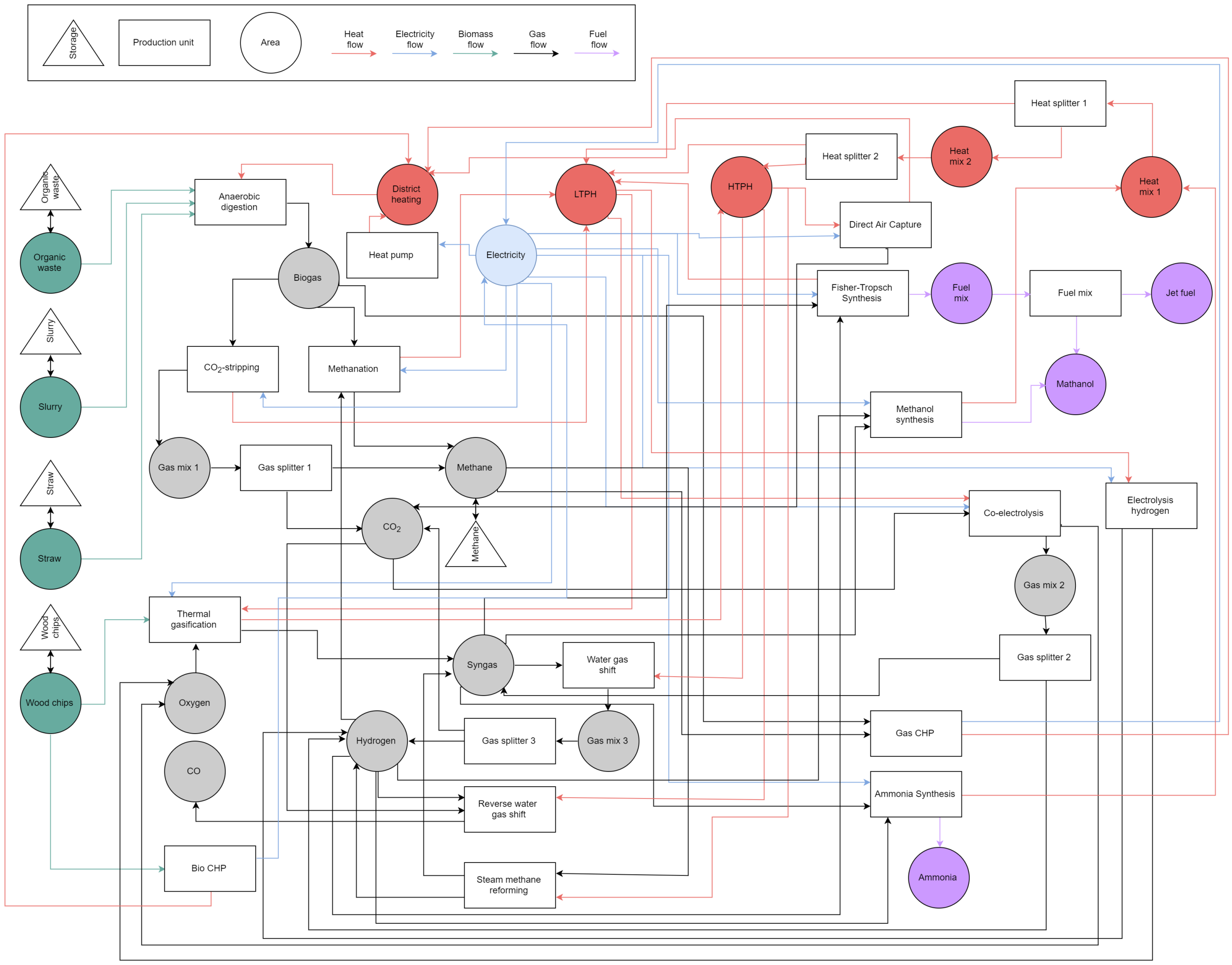


Figure 50: Appendix C: Process flow diagram of energy paths from Sifre set-up. Renewable electricity suppliers are not included in this figure. Detail individual description of process can be found in Appendix A.

C.2 Pre-planed interconnector capacities for electricity and gas in 2050

Table 9: Appendix C: Table showing current planned and existing interconnector capacities in Europe[21][20][19]. The values are used as baseline interconnector capacity in the Sifre Tool

From	**To**	**Gas [MW]**	**Electricity [MW]**	**Sources**
Central	**North**	**9122**	**8000**	
Germany	Denmark	2525	3900	A
Germany	Sweden	0	700	A
Poland	Denmark/Sweden	4200	1000	B
Poland	Lithuania	2397	1000	B
Germany	Norway	0	1400	A
West	**North**	**0**	**5600**	
UK	Denmark	0	1400	A
Netherlands	Denmark	0	700	A
UK	Norway	0	2800	A
Netherlands	Norway	0	700	B
North	**Central**	**36118**	**8000**	
Denmark	Germany	1363	3900	A
Sweden	Germany	0	700	A
Denmark/Sweden	Poland	4200	1000	B
Lithuania	Poland	2397	1000	B
Norway	Germany	28158	1400	A
West	**Central**	**108817**	**4750**	
Netherlands	Germany	95771	750	C
Luxembourg	Germany	0	0	B
France	Germany	0	3000	B
Belgium	Germany	13046	1000	B
South	**Central**	**46613**	**8300**	
Switzerland	Germany	0	1800	B,D
Austria	Germany	26900	4900	E
Austria	Czech Republic	0	700	F
Austria	Slovak Republic	19713	0	F
Hungary	Slovak Republic	0	900	F
North	**West**	**0**	**5600**	
Denmark	UK	0	1400	A
Denmark	Netherlands	0	700	A
Norway	UK	0	2800	A

Norway	Netherlands	0	700	B
Central	**West**	**87483**	**4750**	
Germany	Netherlands	48708	750	C
Germany	Luxembourg	1613	0	B
Germany	France	23825	3000	B
Germany	Belgium	13338	1000	B
South	**West**	**0**	**5600**	
Switzerland	France	0	3100	G
Italy	France	0	2500	G
Central	**South**	**126017**	**8300**	
Germany	Switzerland	23100	1800	B,D
Germany	Austria	27429	4900	E
Czech Republic	Austria	0	700	F
Slovak Republic	Austria	70196	0	F
Slovak Republic	Hungary	5292	900	F
West	**South**	**1558**	**5600**	
France	Switzerland	1558	3100	G
France	Italy	0	2500	G
South East	**South**	**14790**	**10000**	
Bosnia Herzengovina	Croatia	0	5500	B
Serbia	Croatia	0	1400	B
Serbia	Hungary	0	1100	B
Romania	Hungary	104	300	B
Montenegro	Italy	12770	1200	B
Greece	Italy	1916	500	B
South	**South East**	**22752**	**10000**	
Croatia	Bosnia Herzengovina	0	5500	B
Croatia	Serbia	0	1400	B
Hungary	Serbia	5921	1100	B
Hungary	Romania	2146	300	B
Italy	Montenegro	12770	1200	B
Italy	Greece	1916	500	B
A	Nordic Grid development			
B	ENTSO-e power map			
C	TenneT			
D	TYNDP20			

E	Verbund, Together against the split of German-Austrian power price zone
F	PWC, Impediment to electricity trading
G	Electricity and gas interconnections in France p. 21
H	ENSTO-e Electricity interconnections with neighbouring countries

C.3 Fuel distribution allowed in the Sifre tool for different transport sectors

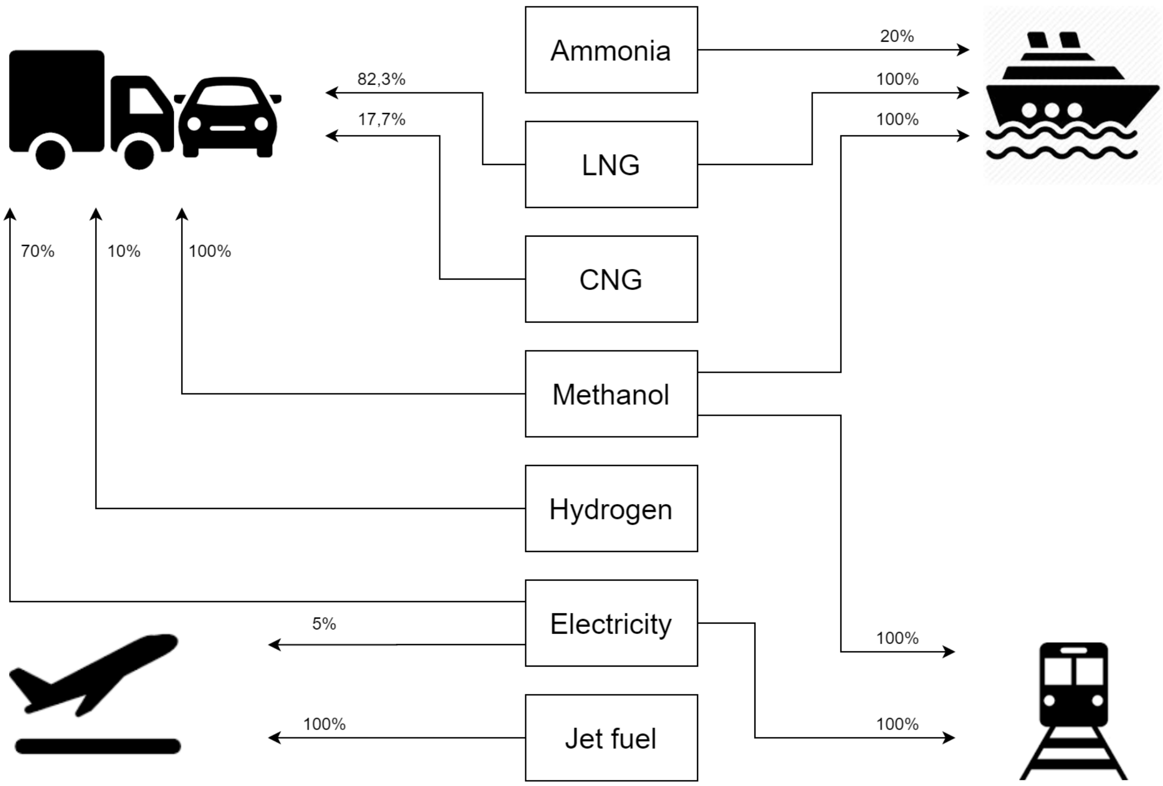


Figure 51: Appendix C: Maximum Fuel inflow allowed in the Sifre tool for different transport sectors.

D Appendices: Sifre Result Extractions

D.1 Methane price - Base Scenario

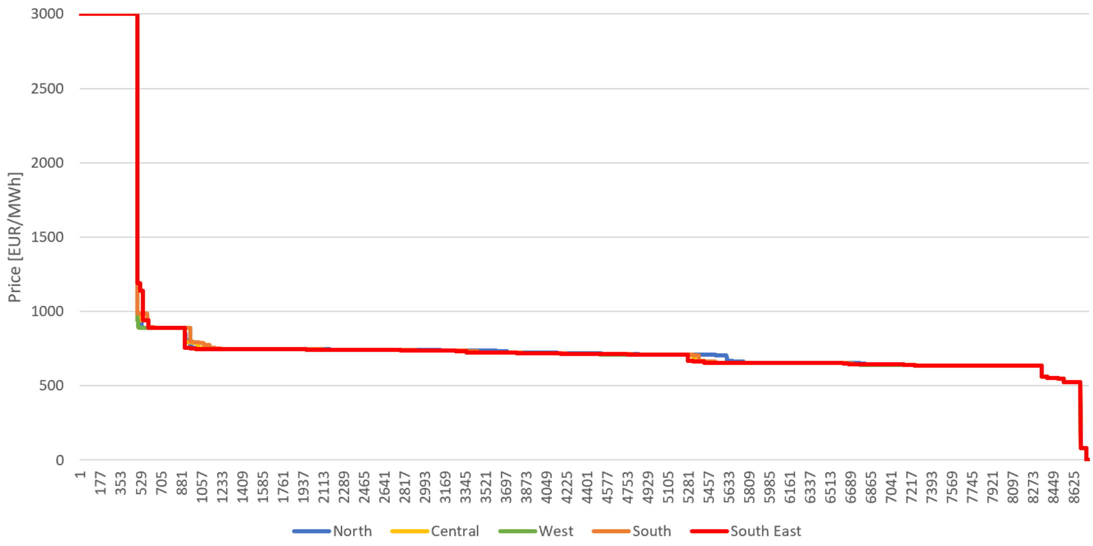


Figure 52: Appendix D: Duration curve showing the Methane Price for the Base Scenario across Europe

D.2 Methane price - Renewable Plus Scenario

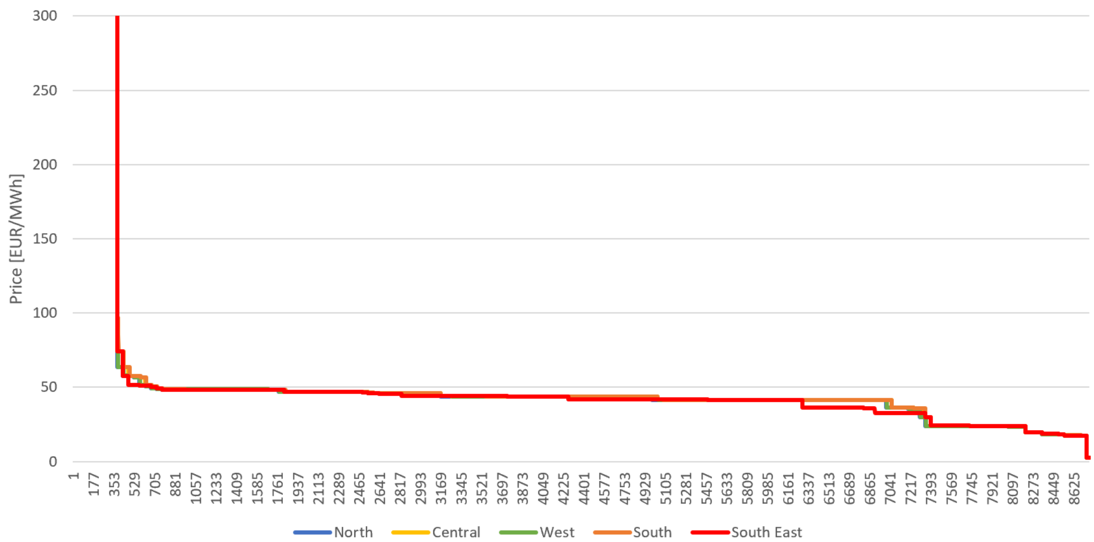


Figure 53: Appendix D: Duration curve showing the Methane Price for the Renewable Plus Scenario across Europe

D.3 Methane price - Interconnector Scenario

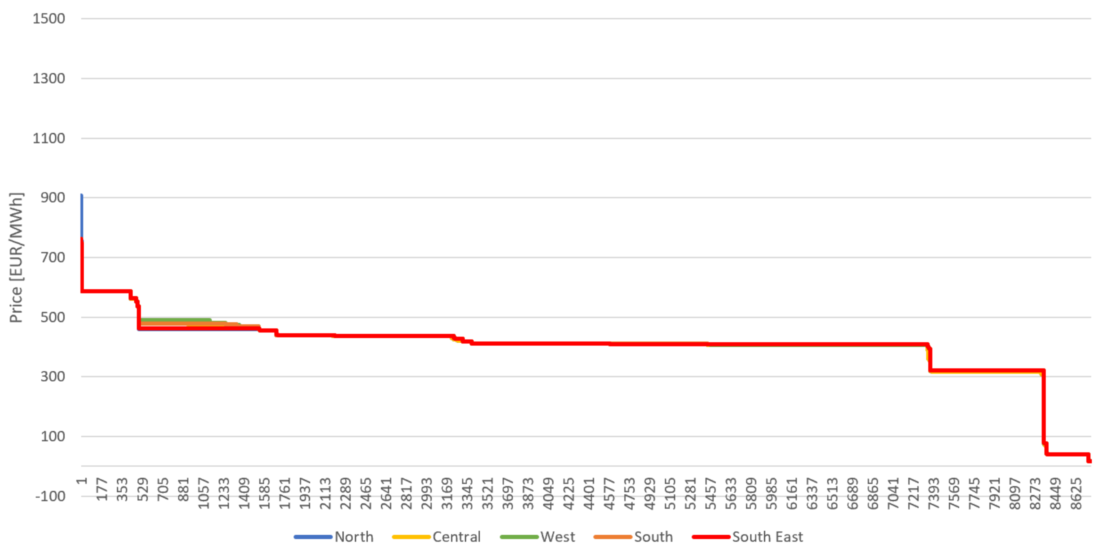


Figure 54: Appendix D: Duration curve showing the Methane Price for the Interconnector Scenario across Europe

D.4 Methane price - Hydrogen Scenario

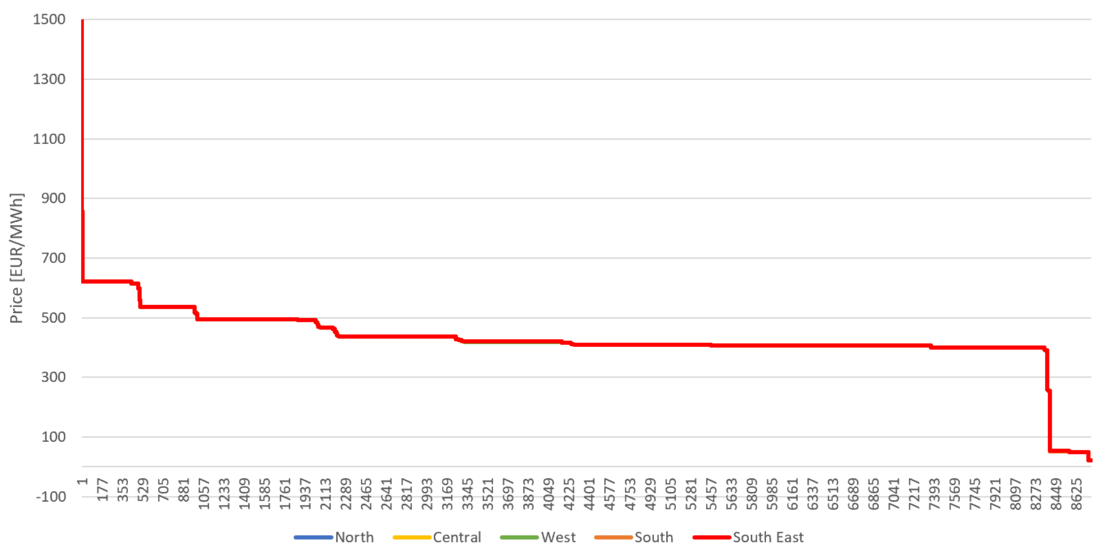


Figure 55: Appendix D: Duration curve showing the Methane Price for the Hydrogen Scenario across Europe

D.5 Hydrogen price - Base Scenario

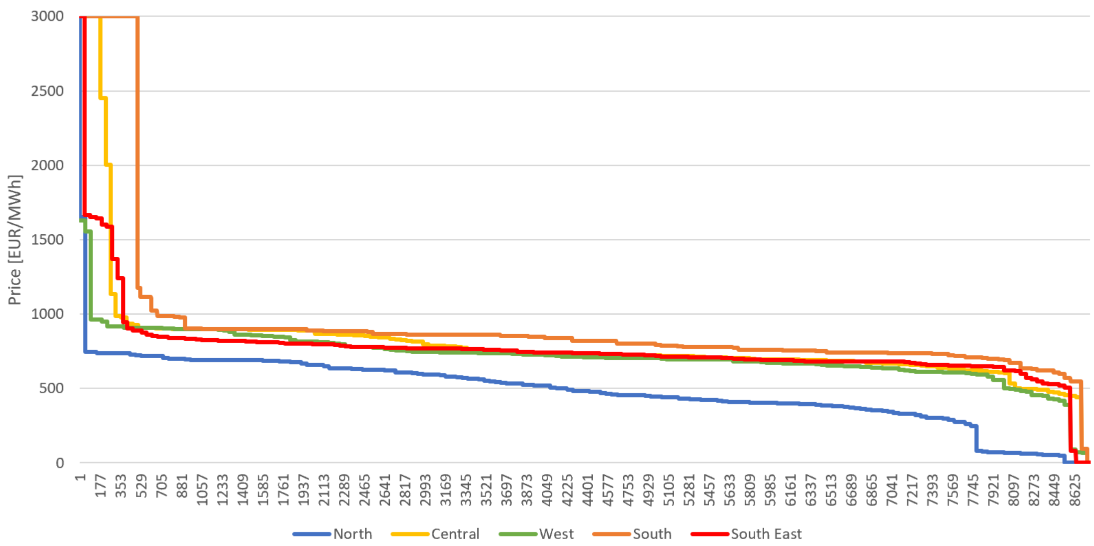


Figure 56: Appendix D: Duration curve showing the Hydrogen Price for the Base Scenario across Europe

D.6 Hydrogen price - Renewable Plus Scenario

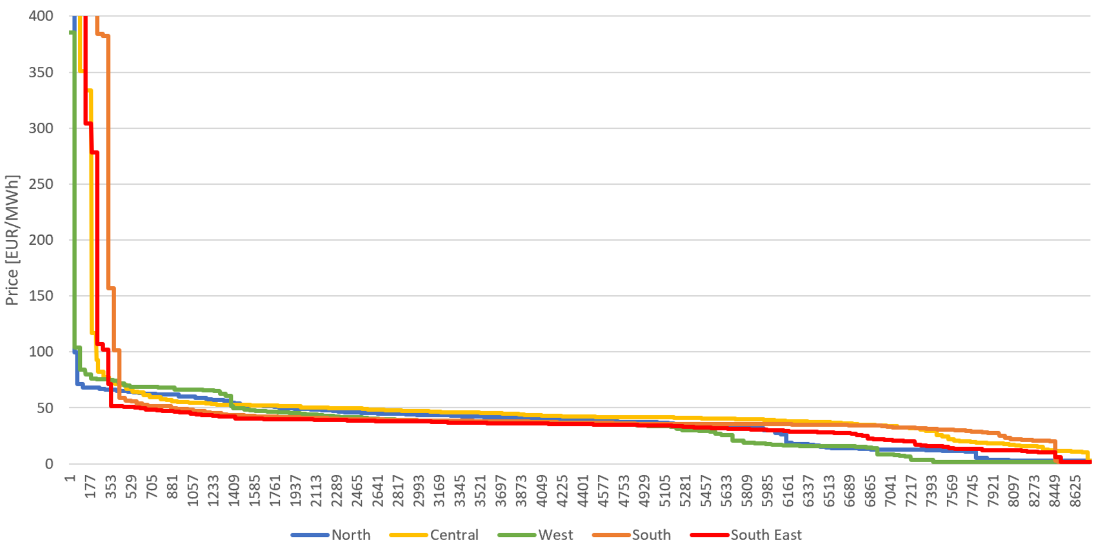


Figure 57: Appendix D: Duration curve showing the Hydrogen Price for the Renewable Plus Scenario across Europe

D.7 Hydrogen price - Interconnector Scenario

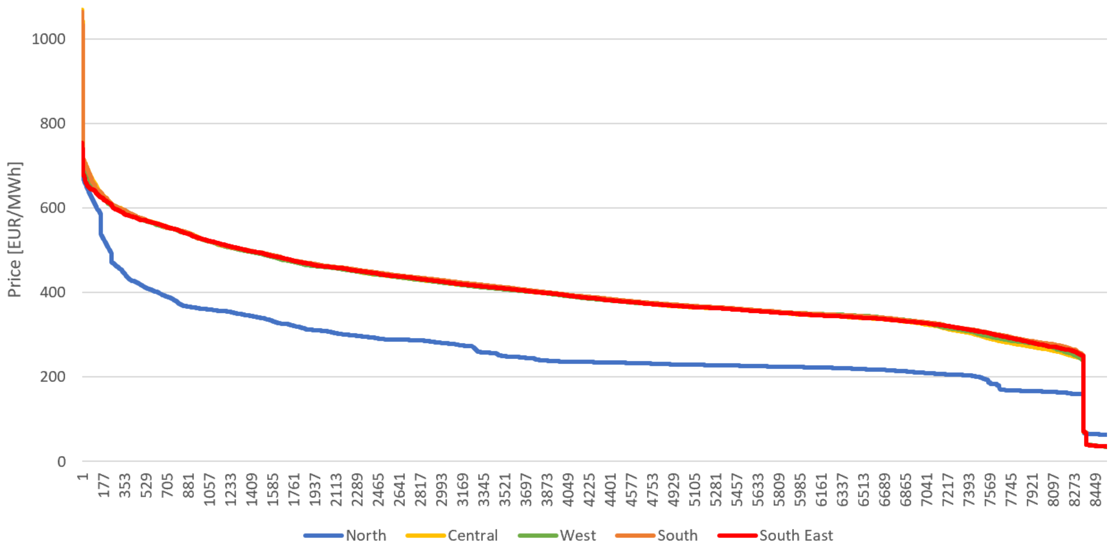


Figure 58: Appendix D: Duration curve showing the Hydrogen Price for the Interconnector Scenario across Europe

D.8 Hydrogen price - Hydrogen Scenario

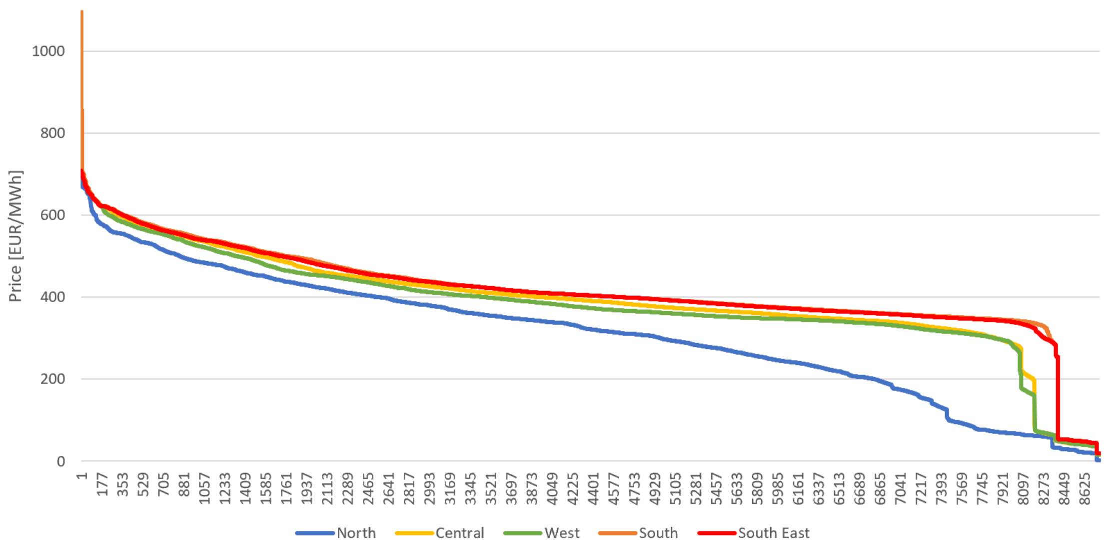


Figure 59: Appendix D: Duration curve showing the Hydrogen Price for the Hydrogen Scenario across Europe

D.9 Invested storage capacity across clusters and Scenarios

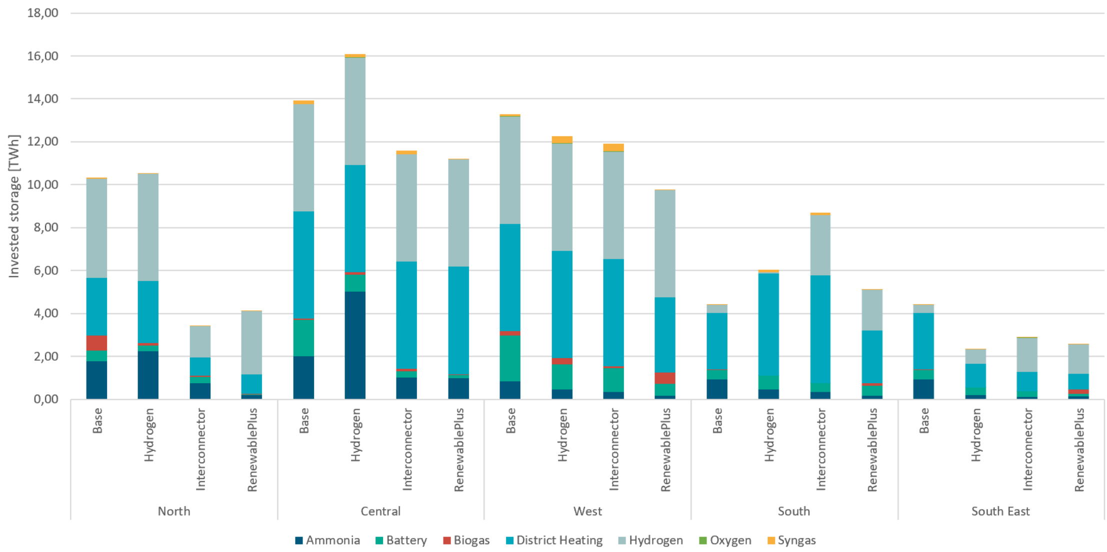


Figure 60: Appendix D: Graph showing the invested storage capacity depending on cluster and Scenario. The figure only includes storage technologies included in the ADAPT investment optimization,

D.10 Fuel distribution in the transport sector across all scenarios and clusters

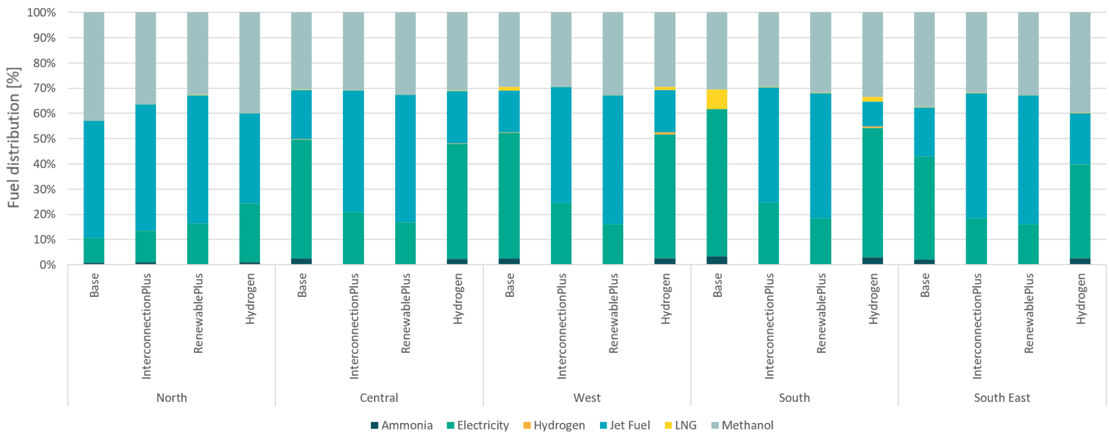


Figure 61: Appendix D: Fuel distribution in the transport sector depending on cluster and scenario

D.11 Fuel distribution in Base Scenario

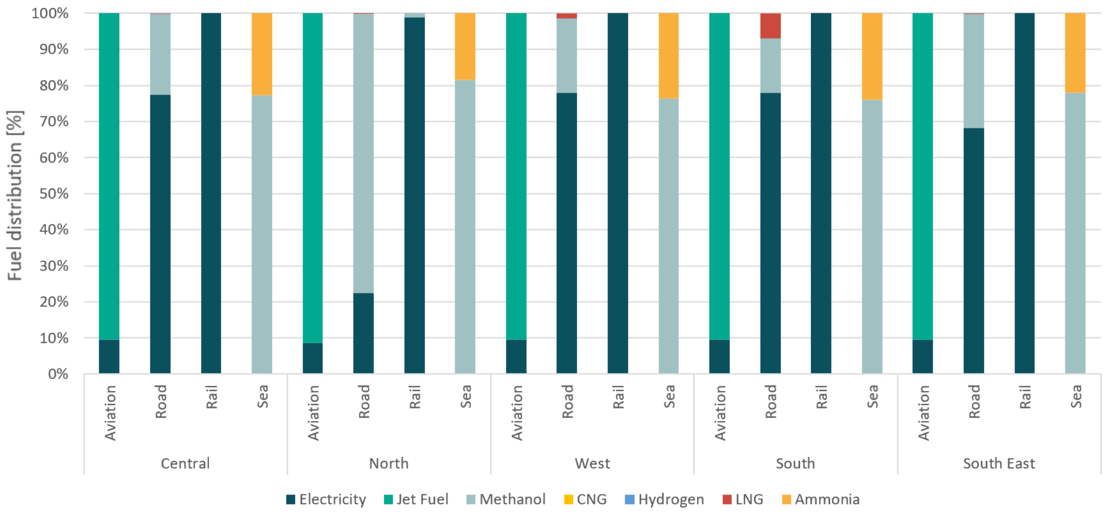


Figure 62: Appendix D: Fuel distribution on different transportation means across Europe in the Base Scenario

D.12 Fuel distribution in Renewable Plus Scenario

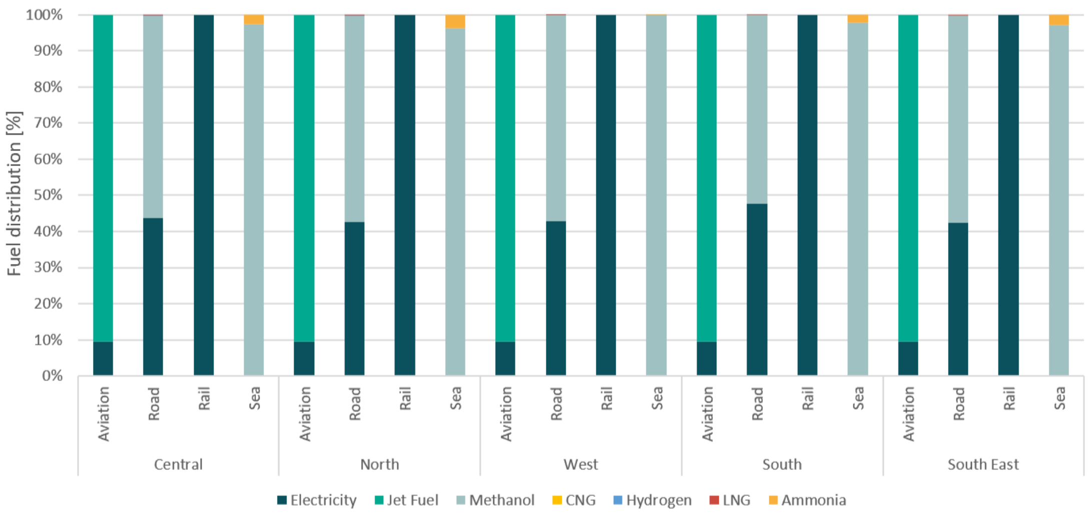


Figure 63: Appendix D: Fuel distribution on different transportation means across Europe in the Renewable Plus Scenario

D.13 Fuel distribution in Interconnector Scenario

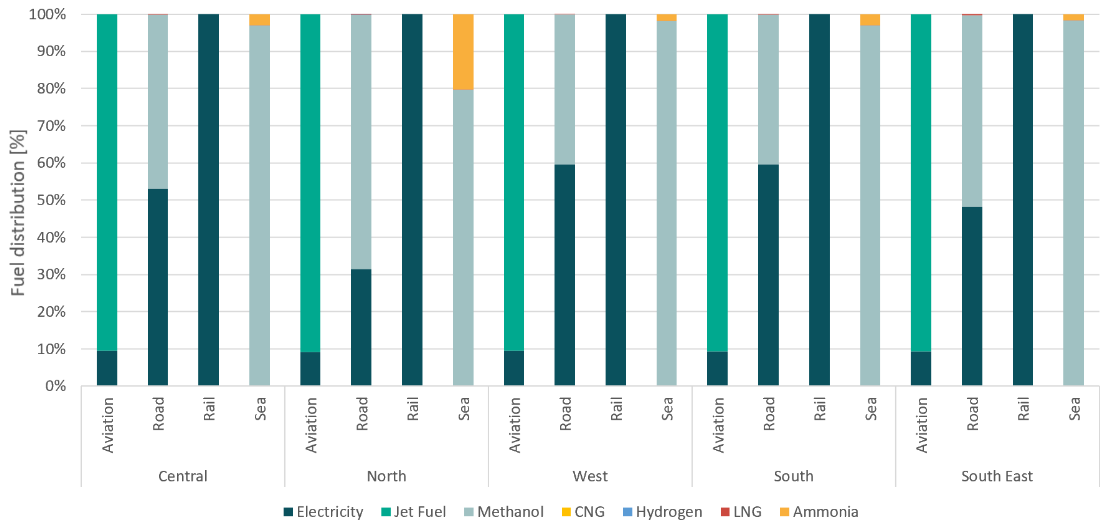


Figure 64: Appendix D: Fuel distribution on different transportation means across Europe in the Interconnector Scenario

D.14 Fuel distribution in Hydrogen Scenario

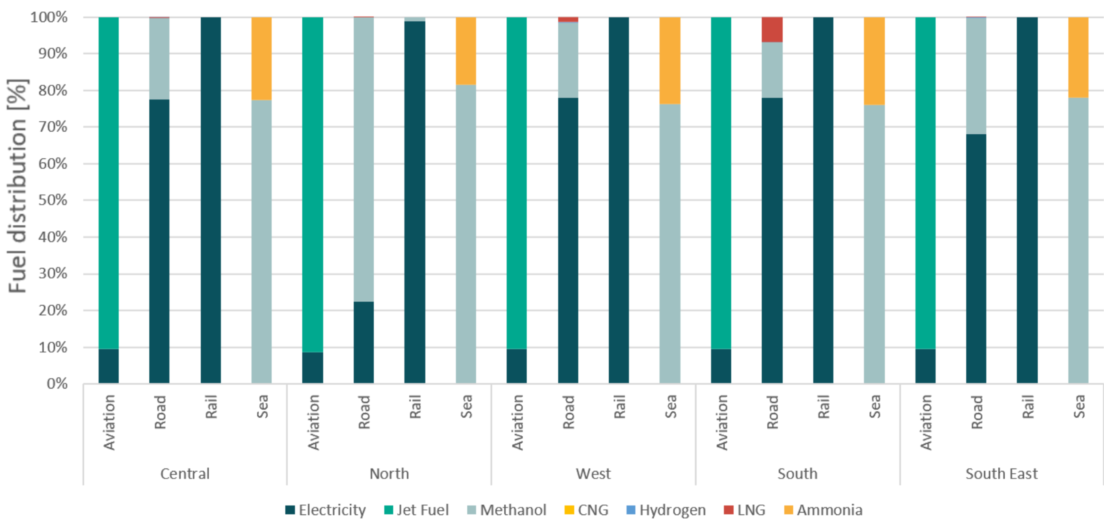


Figure 65: Appendix D: Fuel distribution on different transportation means across Europe in the Hydrogen Scenario

D.15 Bottleneck revenues in the five clusters in the four simulation scenarios

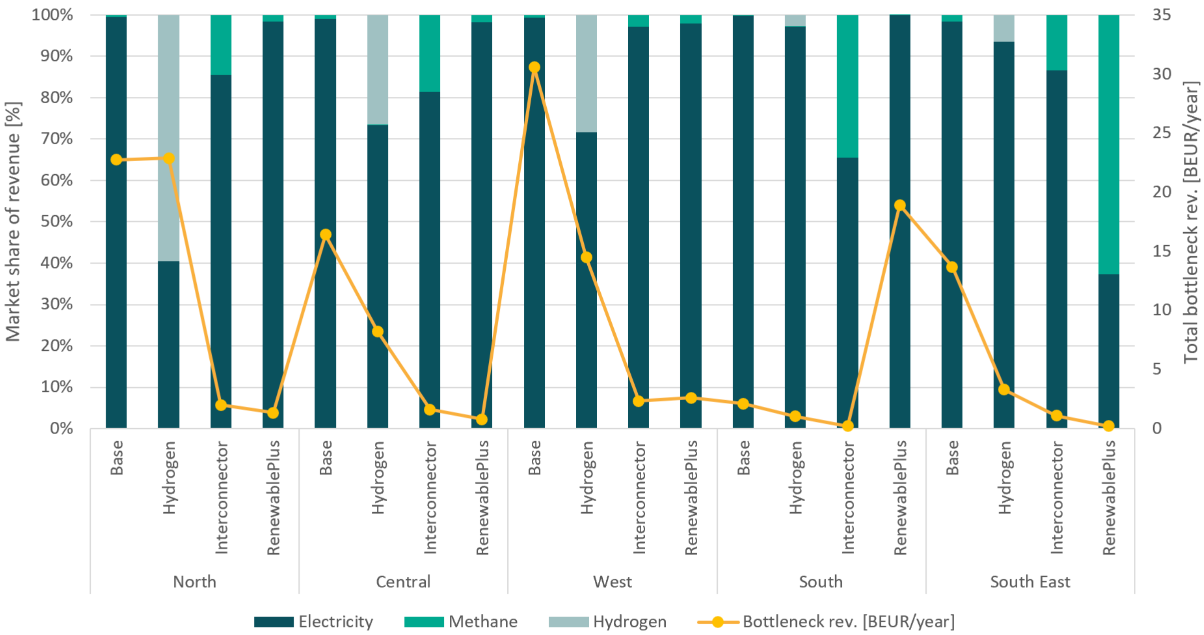


Figure 66: Appendix D: The bottleneck revenues of selling electricity, methane, and hydrogen across clusters in the four simulation scenarios.

E Appendices: Sankey Diagrams

E.1 Sankey Diagram of North Europe Base Scenario

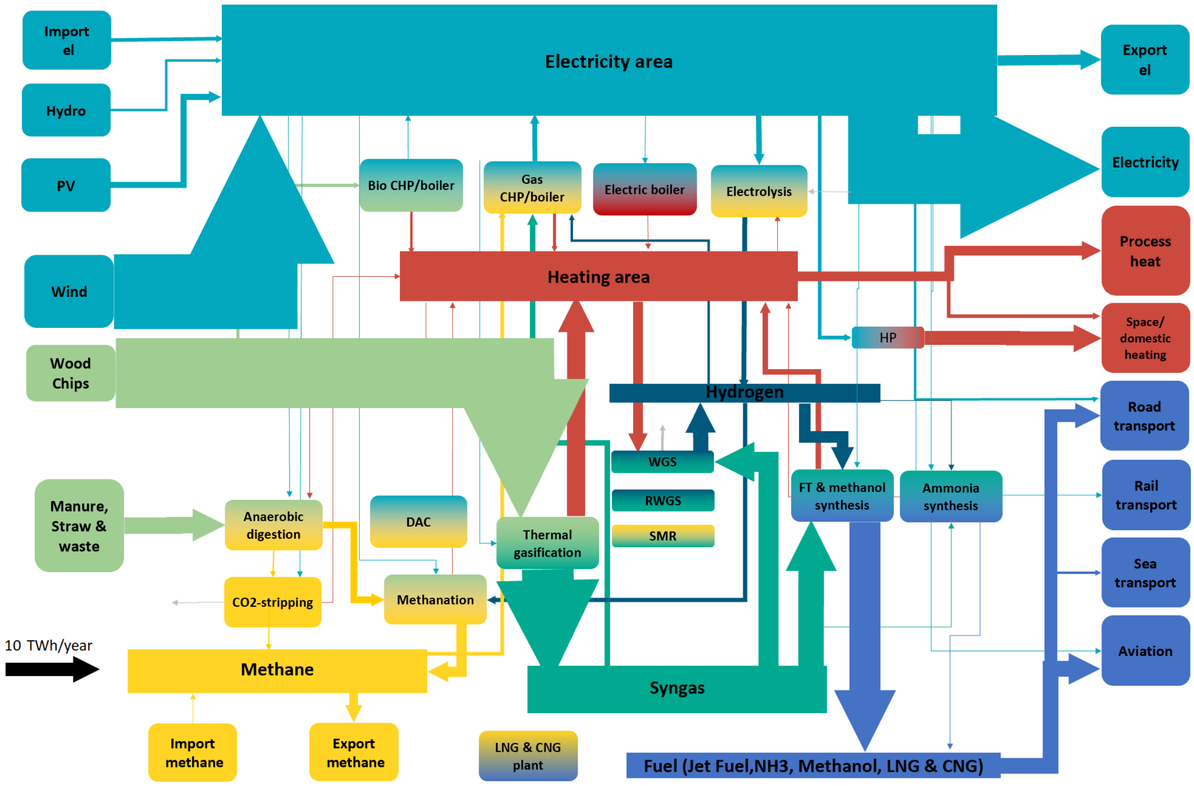


Figure 67: Appendix E: Sankey Diagram showing energy flows in North Europe in the Base Scenario

E.2 Sankey Diagram of Central Europe Base Scenario

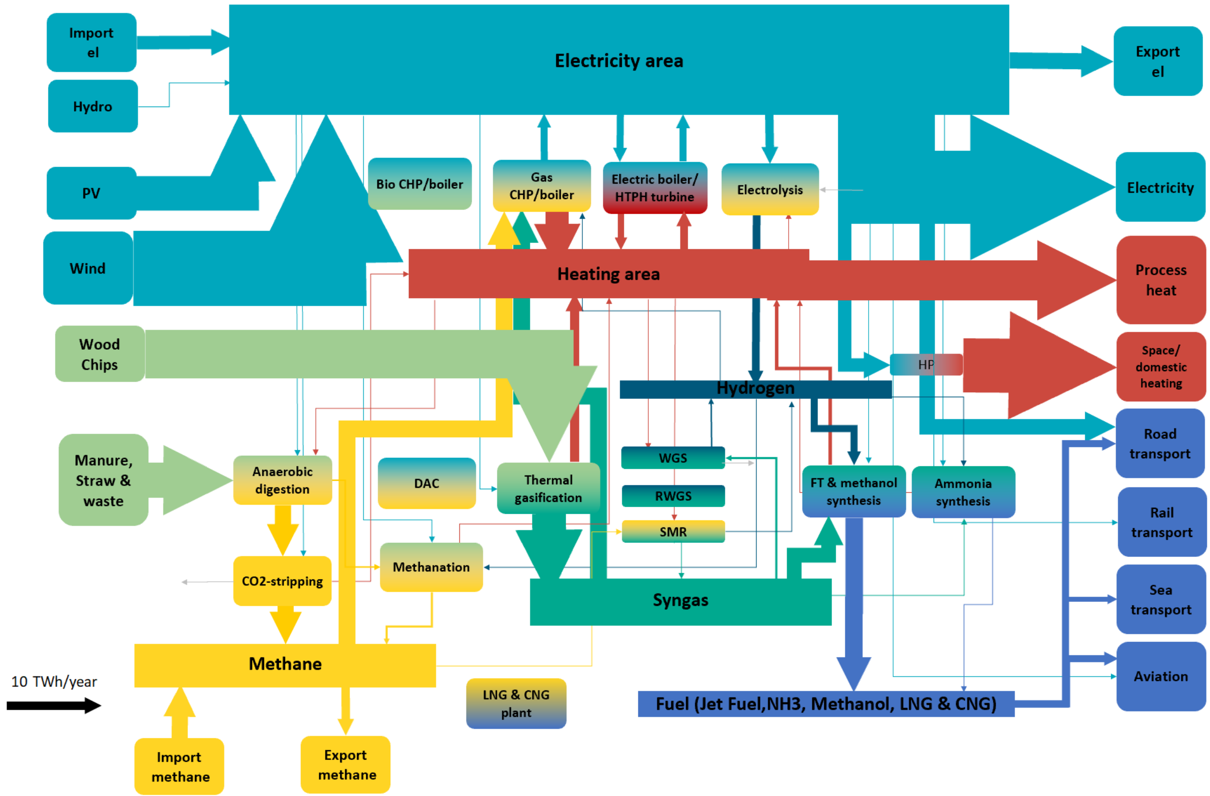


Figure 68: Appendix E: Sankey Diagram showing energy flows in Central Europe in the Base Scenario

E.3 Sankey Diagram of West Europe Base Scenario

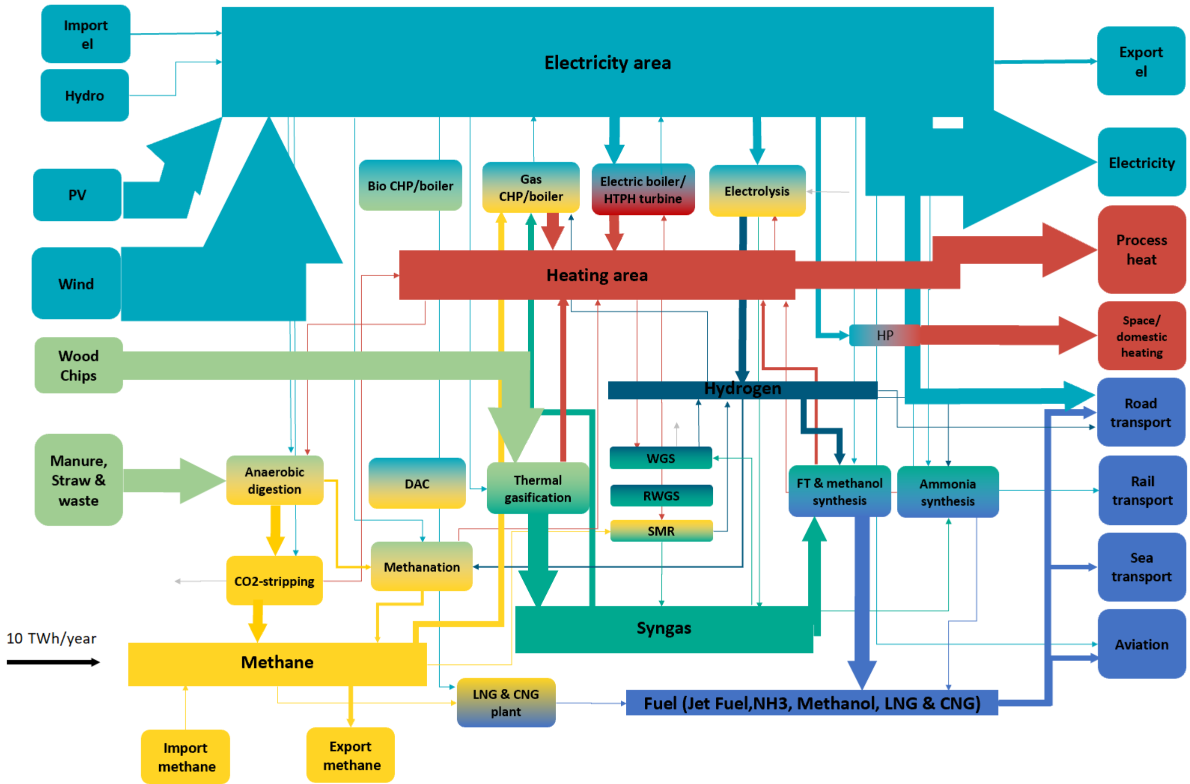


Figure 69: Appendix E: Sankey Diagram showing energy flows in West Europe in the Base Scenario

E.4 Sankey Diagram of South Europe Base Scenario

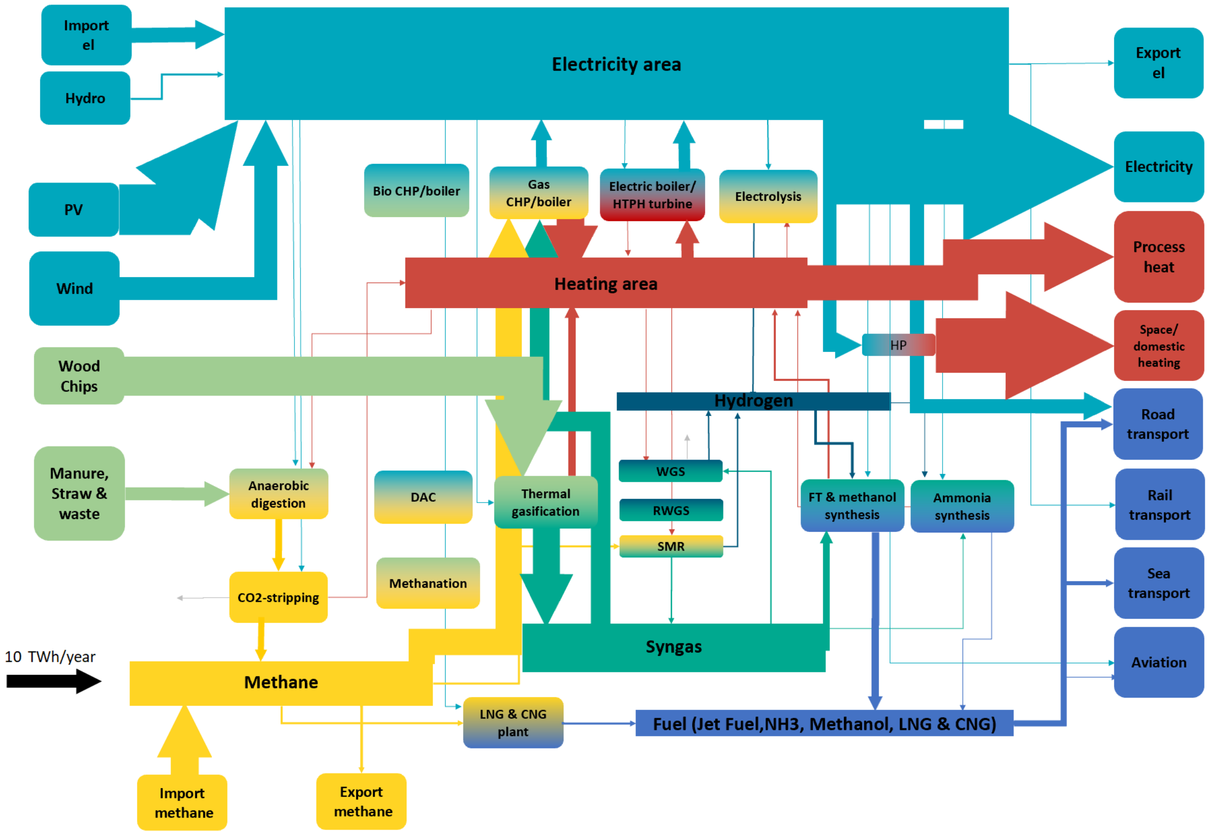


Figure 70: Appendix E: Sankey Diagram showing energy flows in South Europe in the Base Scenario

E.5 Sankey Diagram of South East Europe Base Scenario

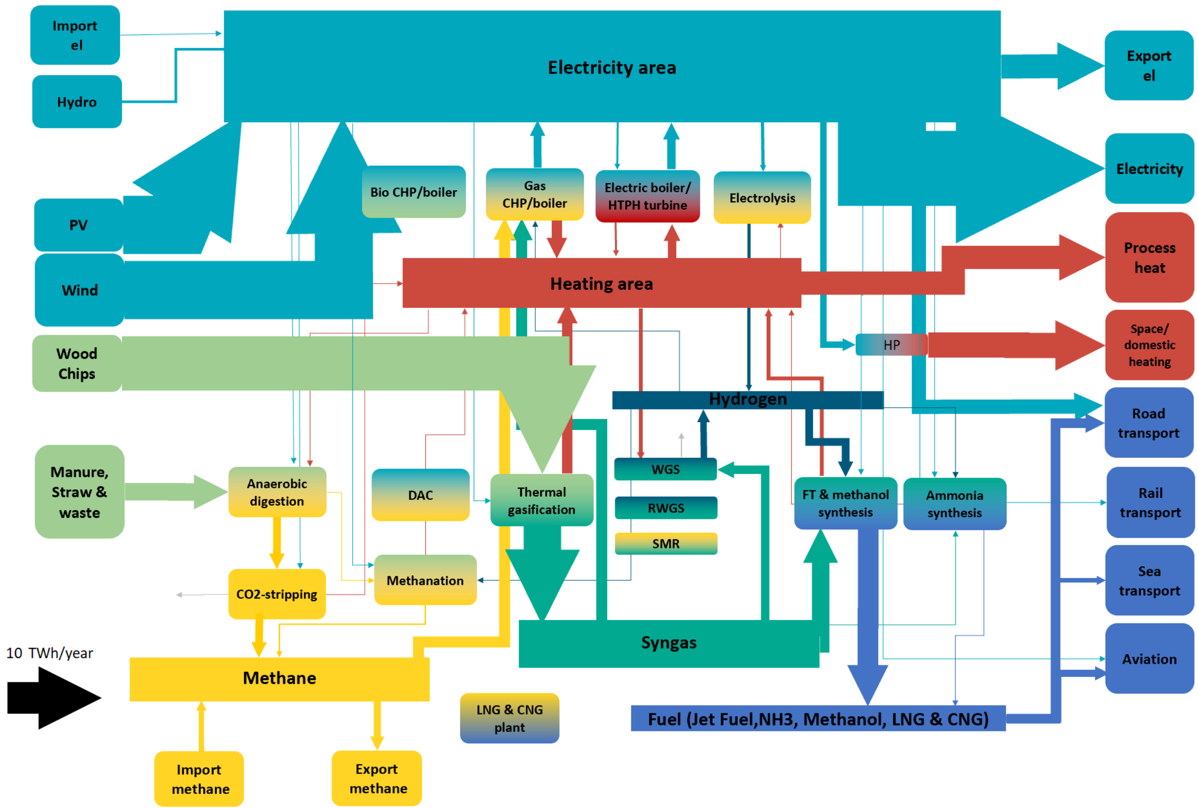


Figure 71: Appendix E: Sankey Diagram showing energy flows in South East Europe in the Base Scenario

E.6 Sankey Diagram of North Europe Renewable Plus Scenario

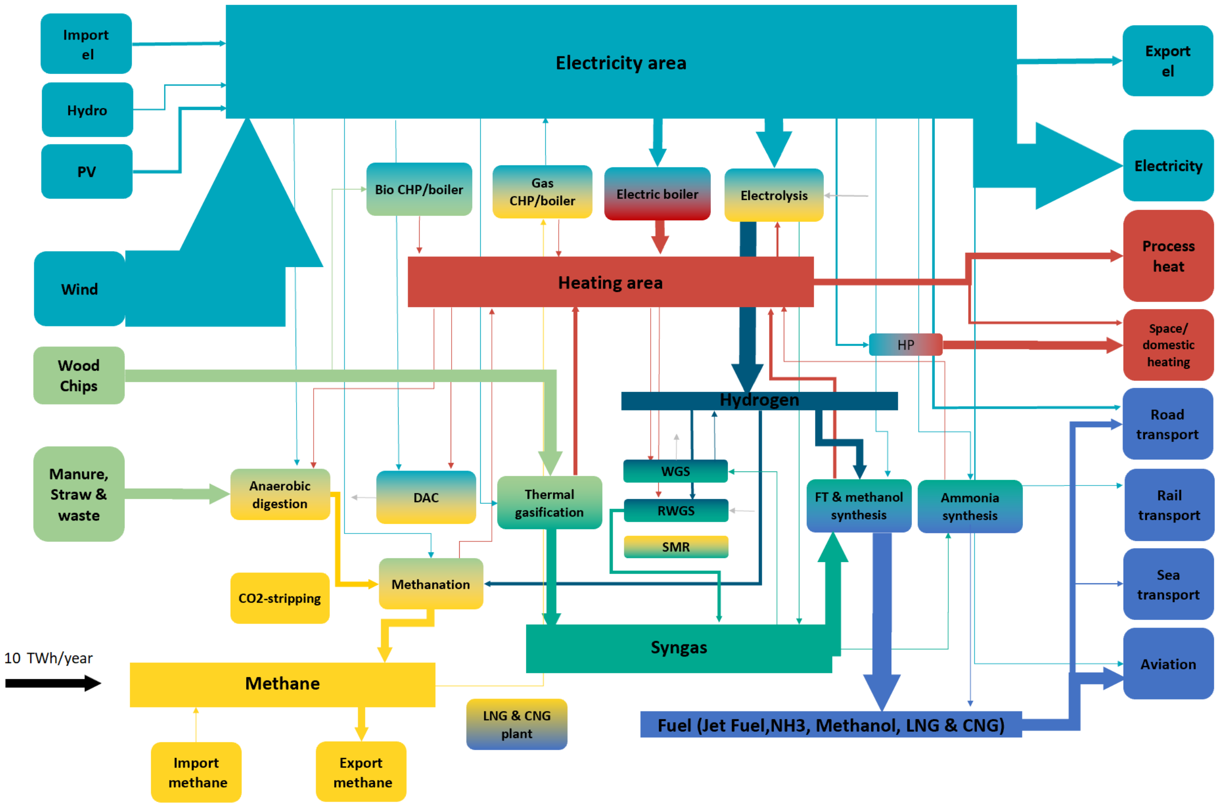


Figure 72: Appendix E: Sankey Diagram showing energy flows in North Europe in the Renewable Plus Scenario

E.7 Sankey Diagram of Central Europe Renewable Plus Scenario

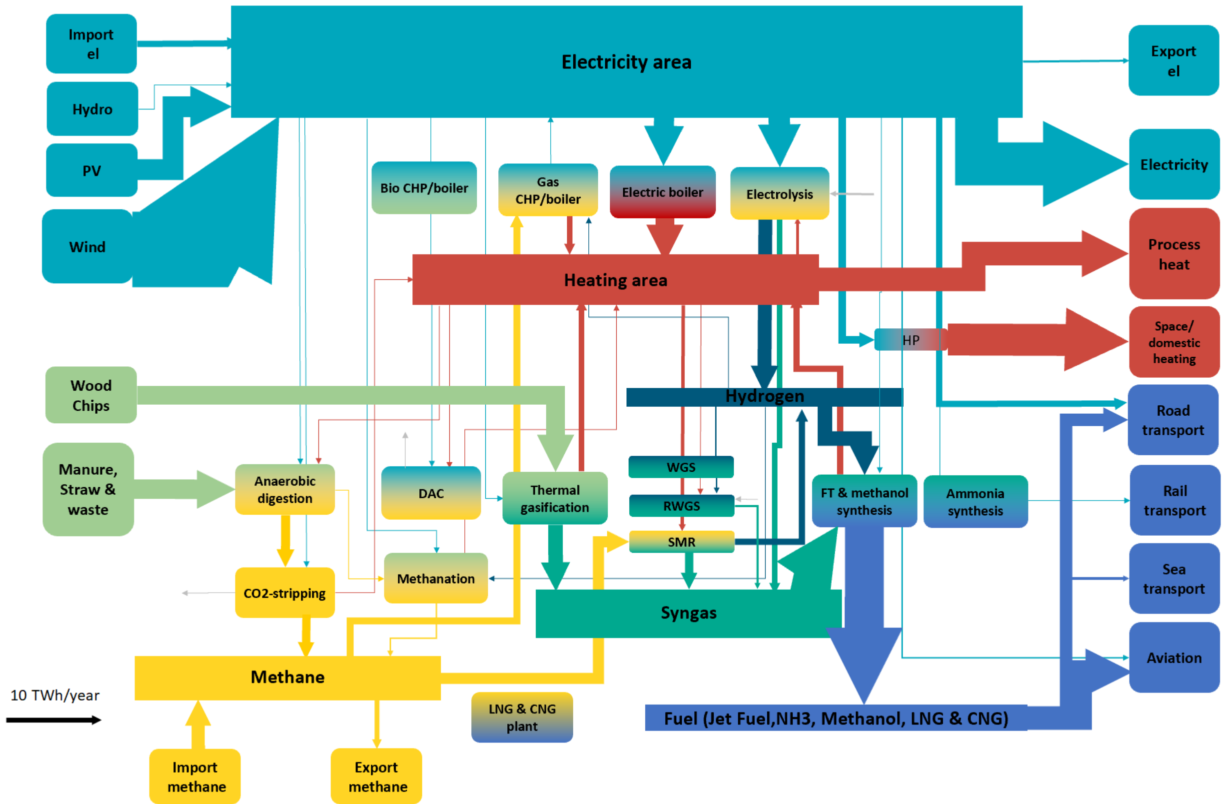


Figure 73: Appendix E: Sankey Diagram showing energy flows in Central Europe in the Renewable Plus Scenario

E.8 Sankey Diagram of West Europe Renewable Plus Scenario

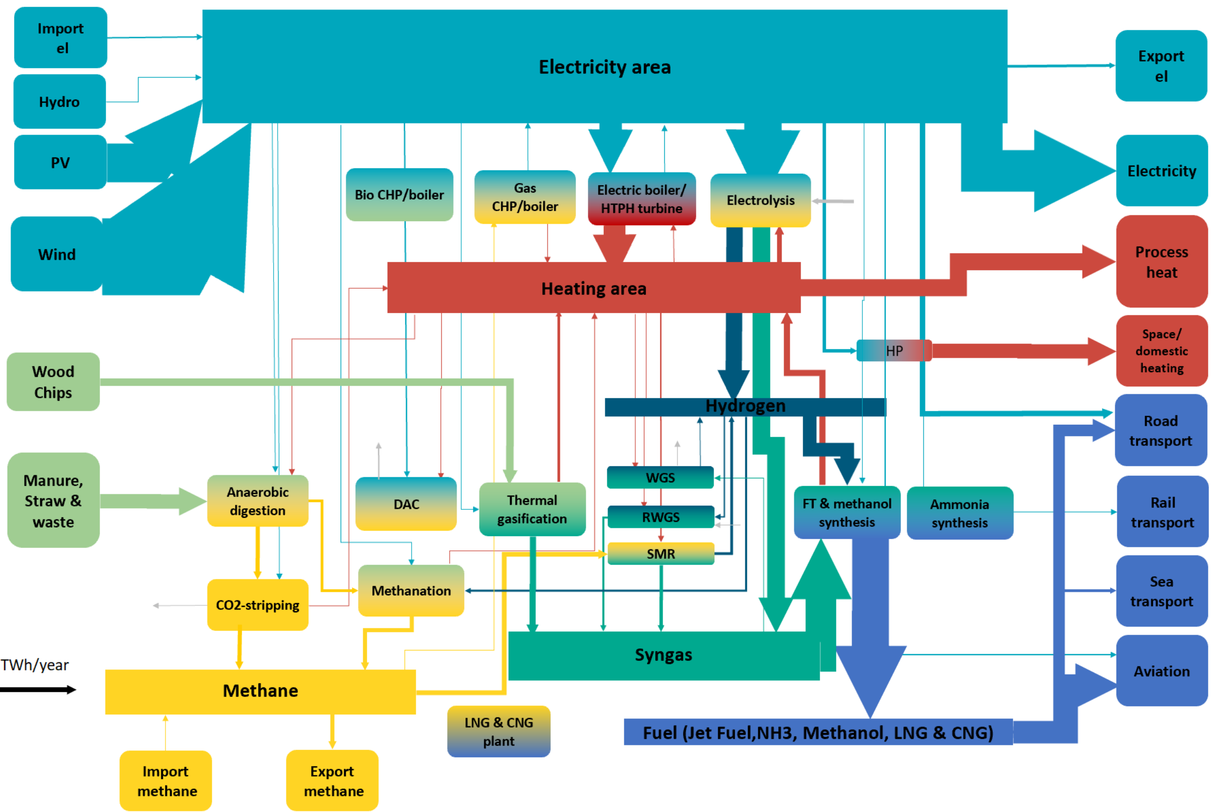


Figure 74: Appendix E: Sankey Diagram showing energy flows in West Europe in the Renewable Plus Scenario

E.9 Sankey Diagram of South Europe Renewable Plus Scenario

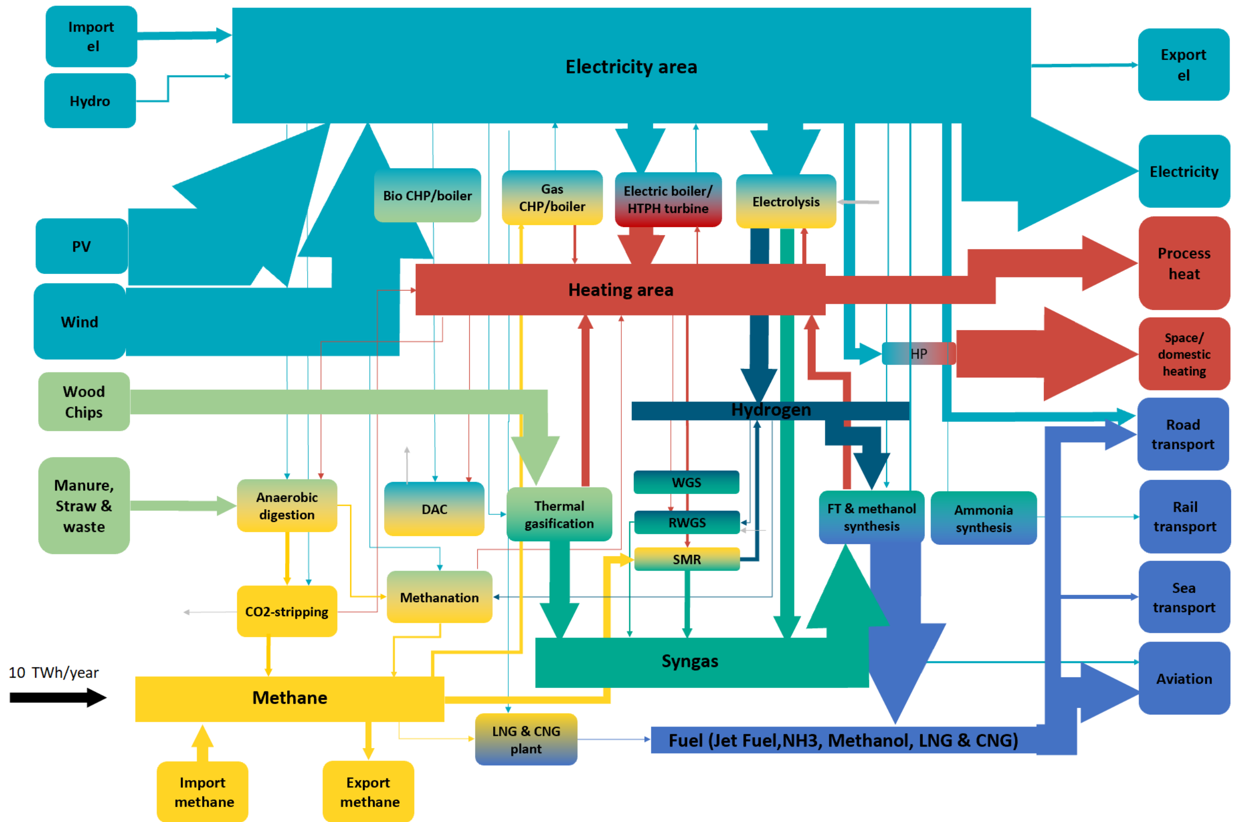


Figure 75: Appendix E: Sankey Diagram showing energy flows in South Europe in the Renewable Plus Scenario

E.10 Sankey Diagram of South East Europe Renewable Plus Scenario

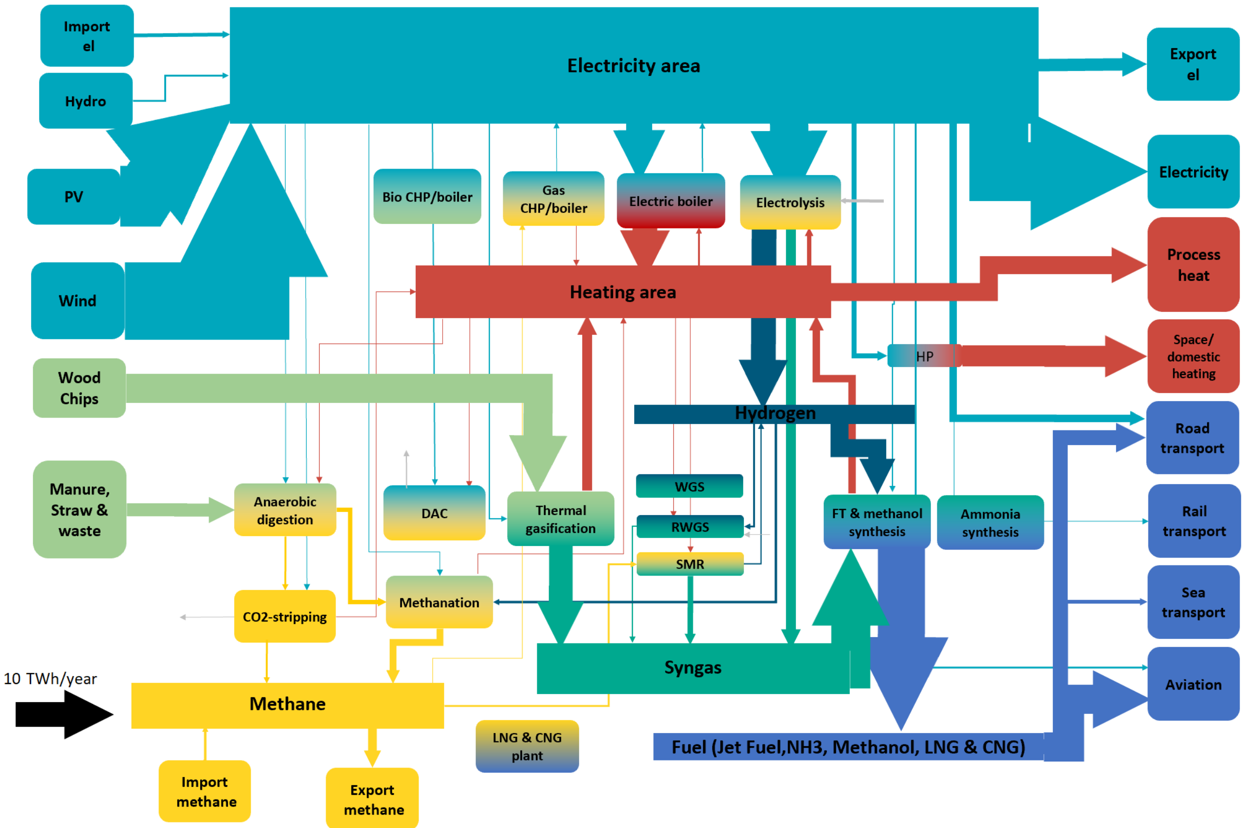


Figure 76: Appendix E: Sankey Diagram showing energy flows in South East Europe in the Renewable Plus Scenario

E.11 Sankey Diagram of North Europe Interconnection Scenario

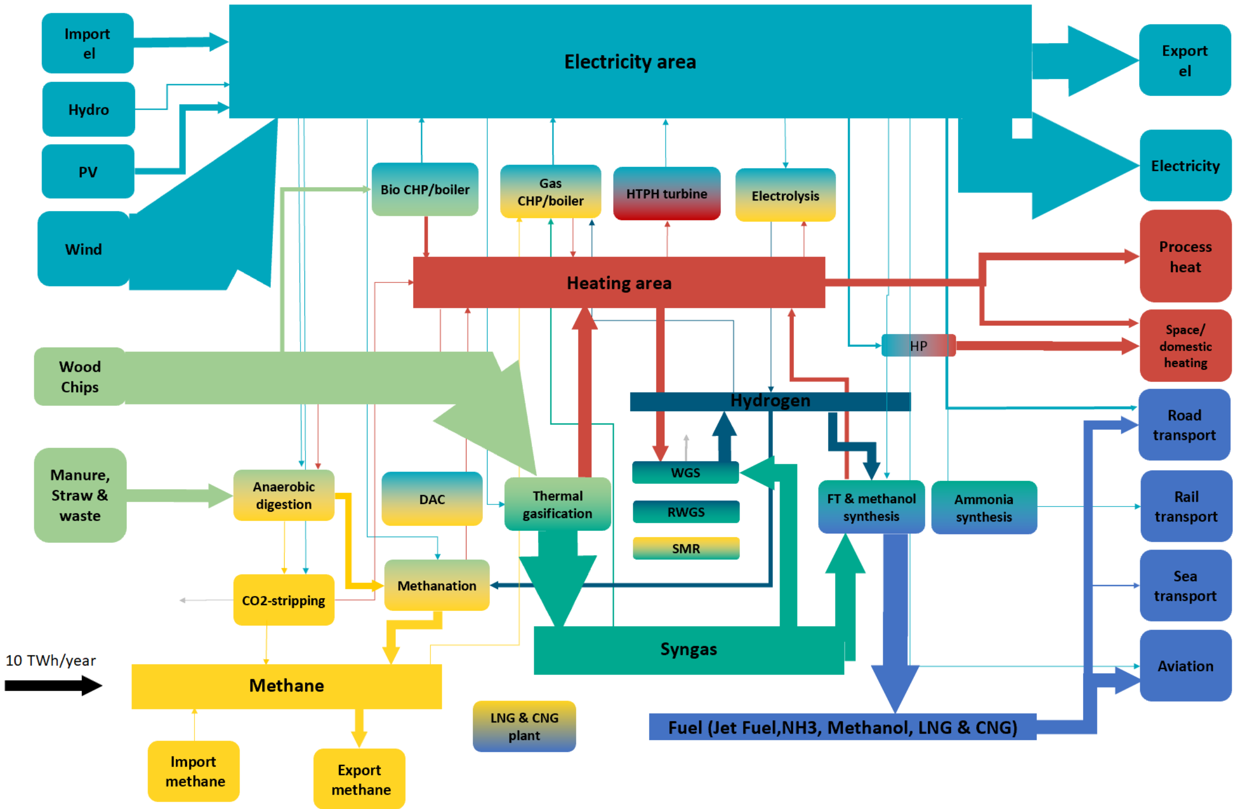


Figure 77: Appendix E: Sankey Diagram showing energy flows in North Europe in the Interconnector Scenario

E.12 Sankey Diagram of Central Europe Interconnection Scenario

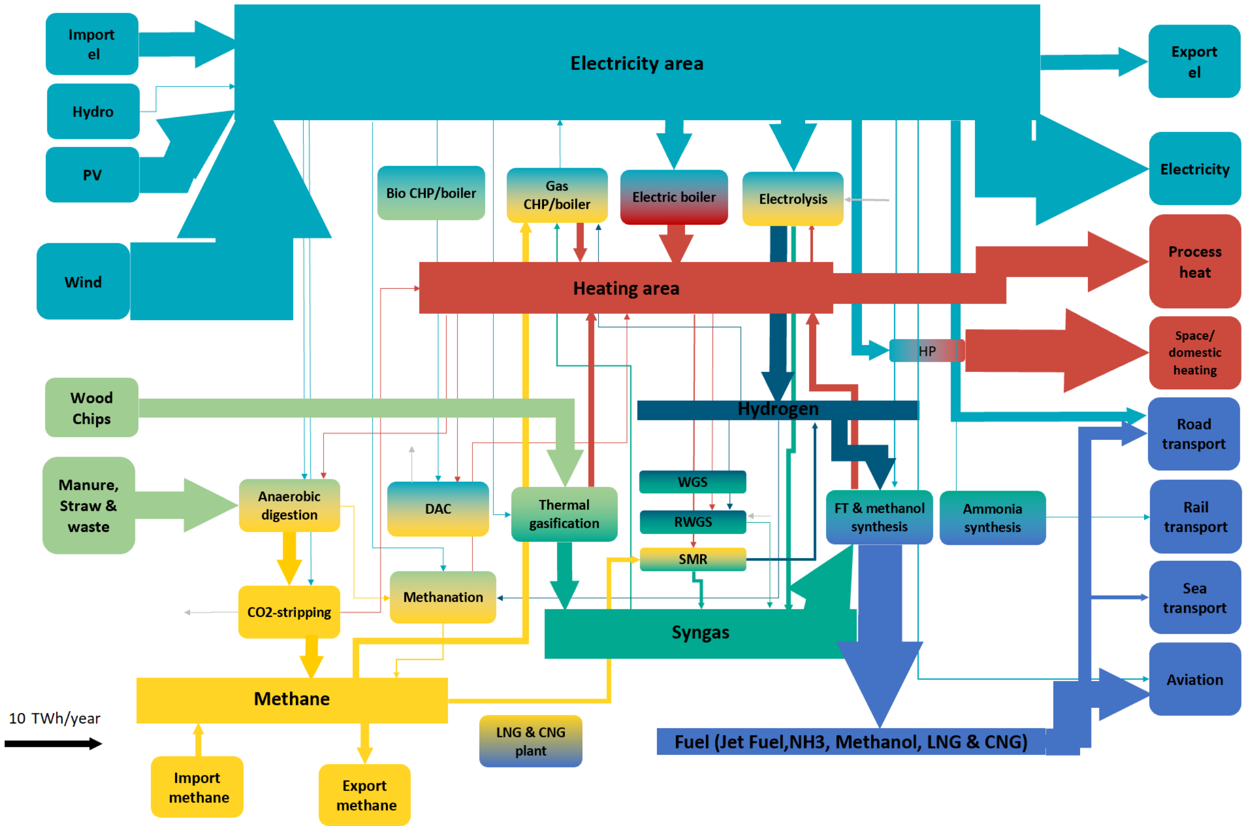


Figure 78: Appendix E: Sankey Diagram showing energy flows in Central Europe in the Interconnector Scenario

E.13 Sankey Diagram of West Europe Interconnection Scenario

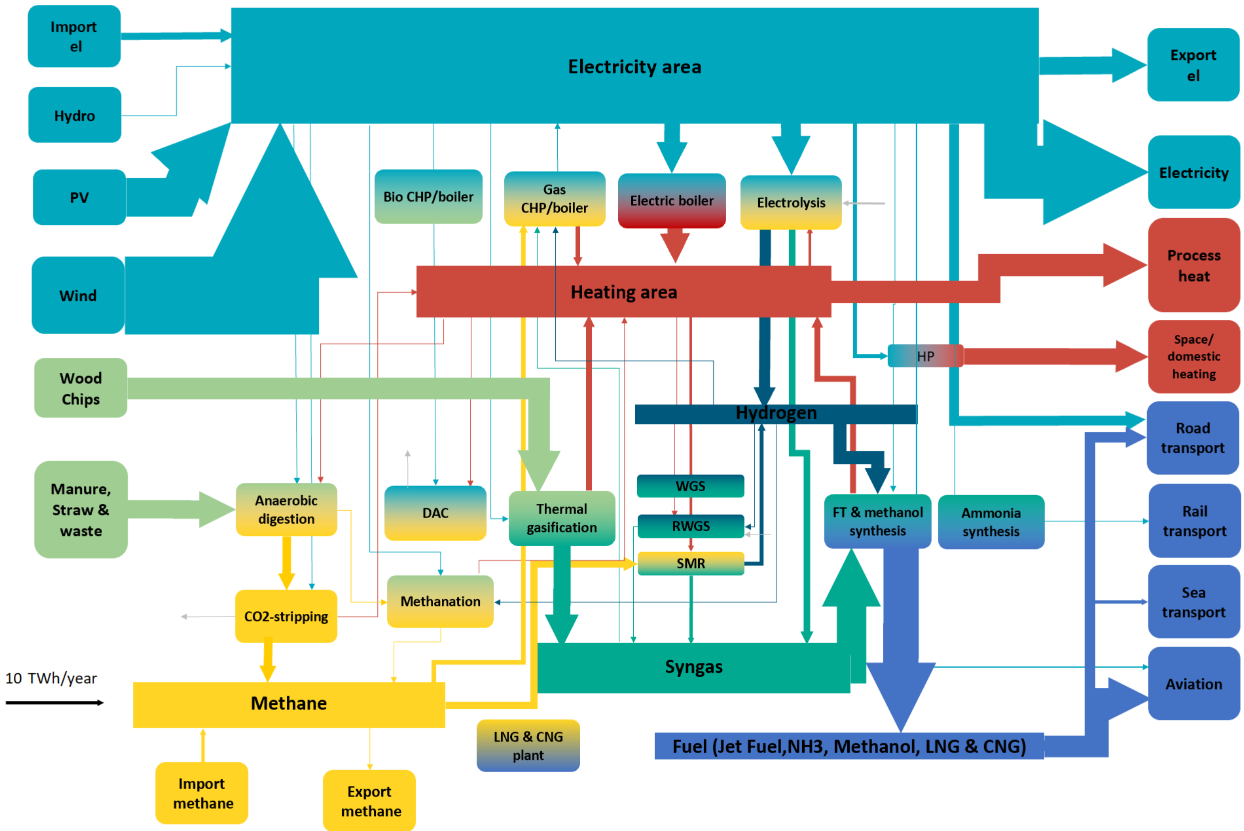


Figure 79: Appendix E: Sankey Diagram showing energy flows in West Europe in the Interconnector Scenario

E.14 Sankey Diagram of South Europe Interconnection Scenario

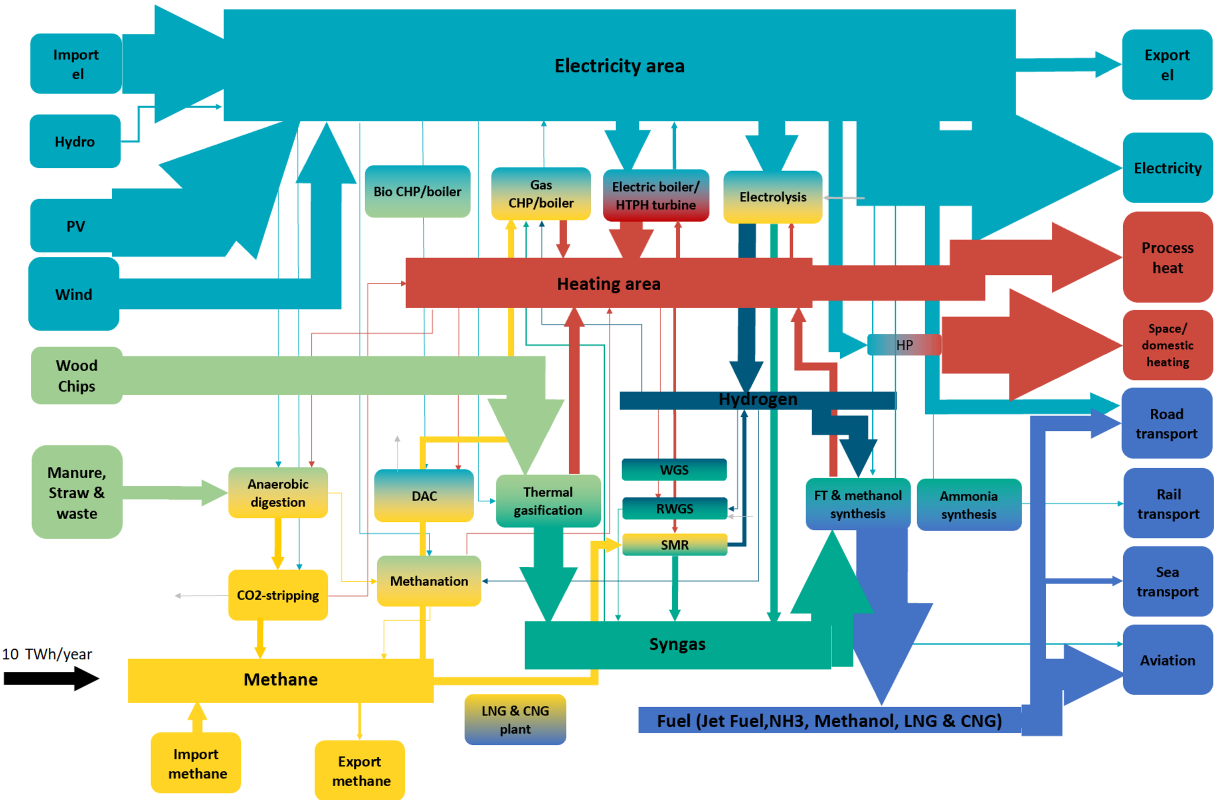


Figure 80: Appendix E: Sankey Diagram showing energy flows in South Europe in the Interconnector Scenario

E.15 Sankey Diagram of South East Europe Interconnection Scenario

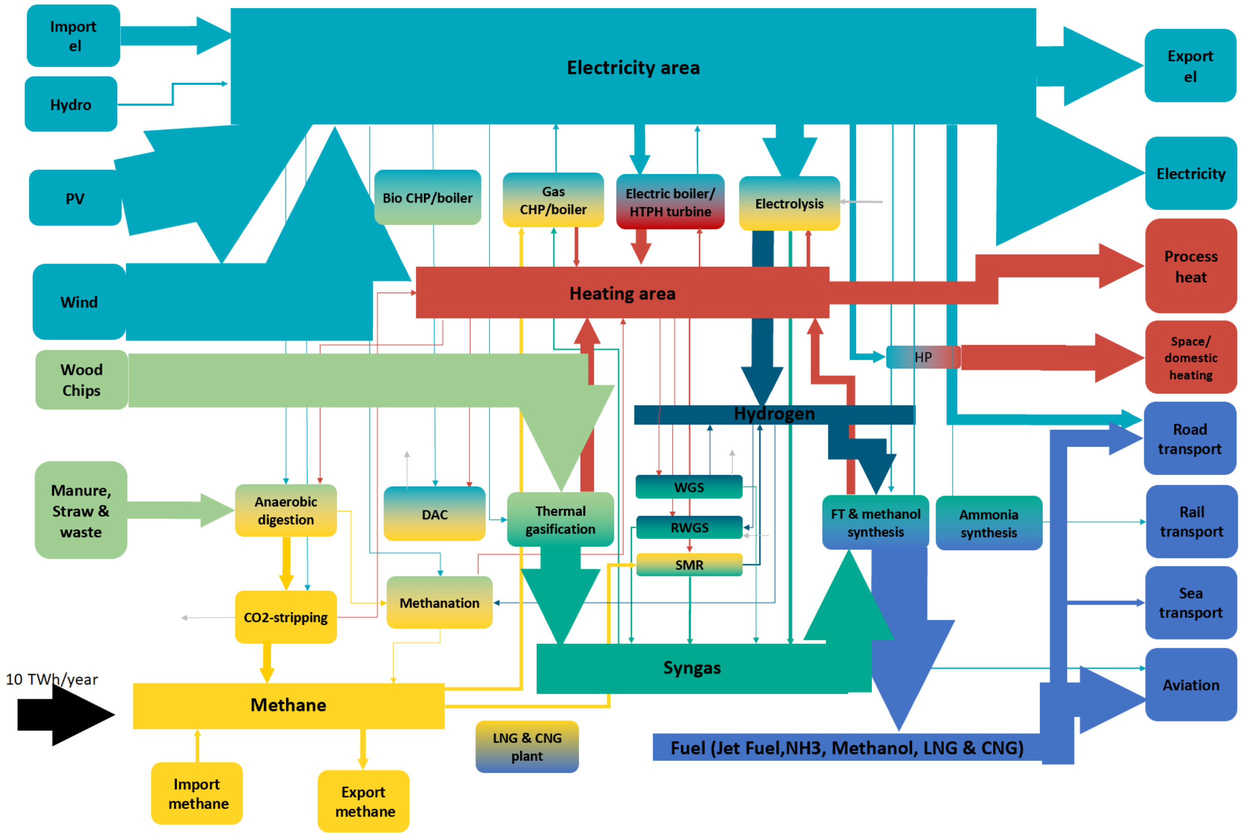


Figure 81: Appendix E: Sankey Diagram showing energy flows in South East Europe in the Interconnector Scenario

E.16 Sankey Diagram of North Europe Hydrogen Scenario

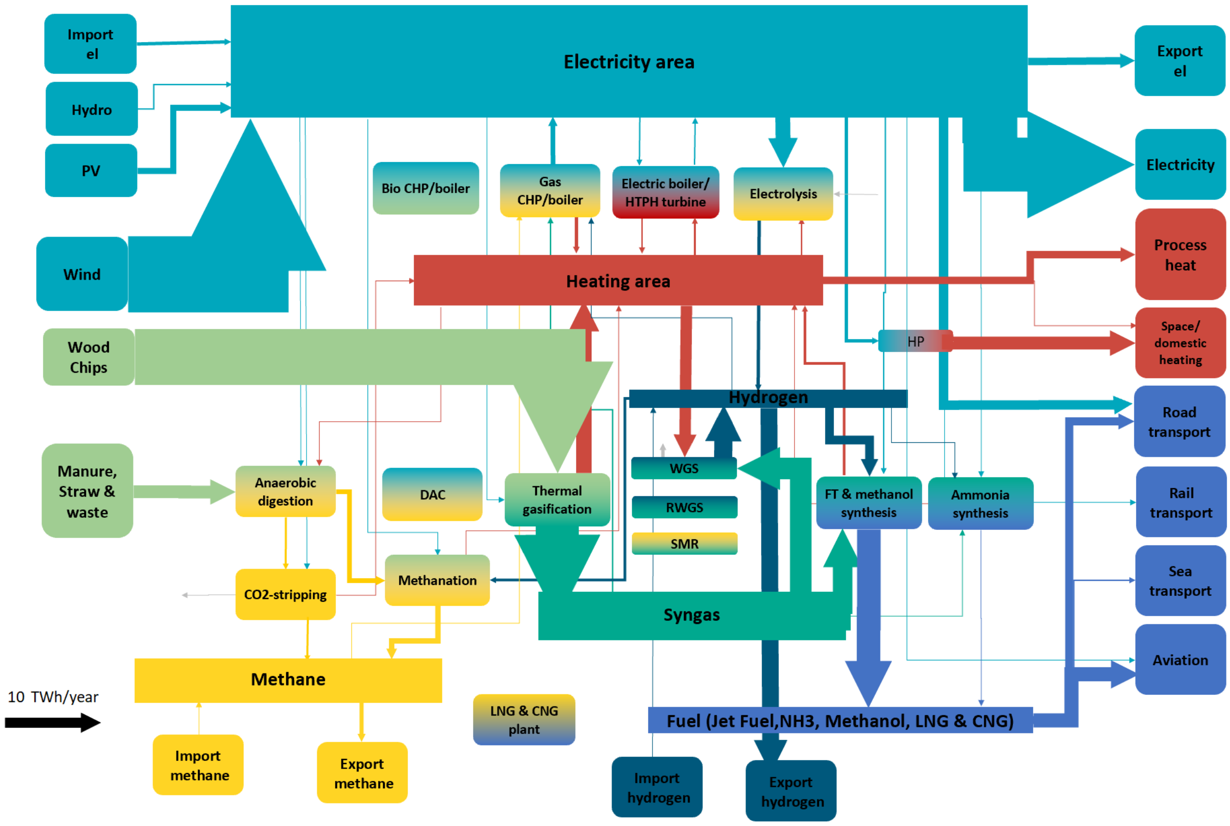


Figure 82: Appendix E: Sankey Diagram showing energy flows in North Europe in the Hydrogen Scenario

E.17 Sankey Diagram of Central Europe Hydrogen Scenario

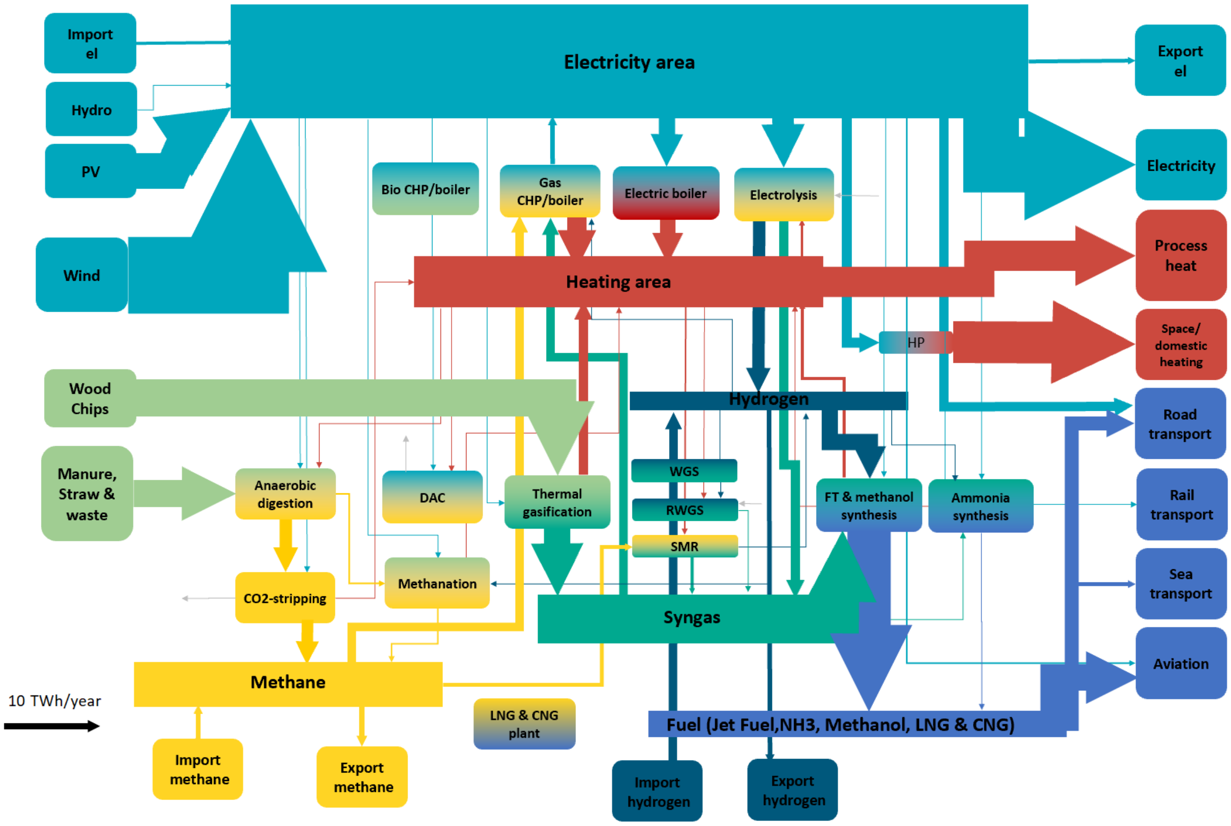


Figure 83: Appendix E: Sankey Diagram showing energy flows in Central Europe in the Hydrogen Scenario

E.18 Sankey Diagram of West Europe Hydrogen Scenario

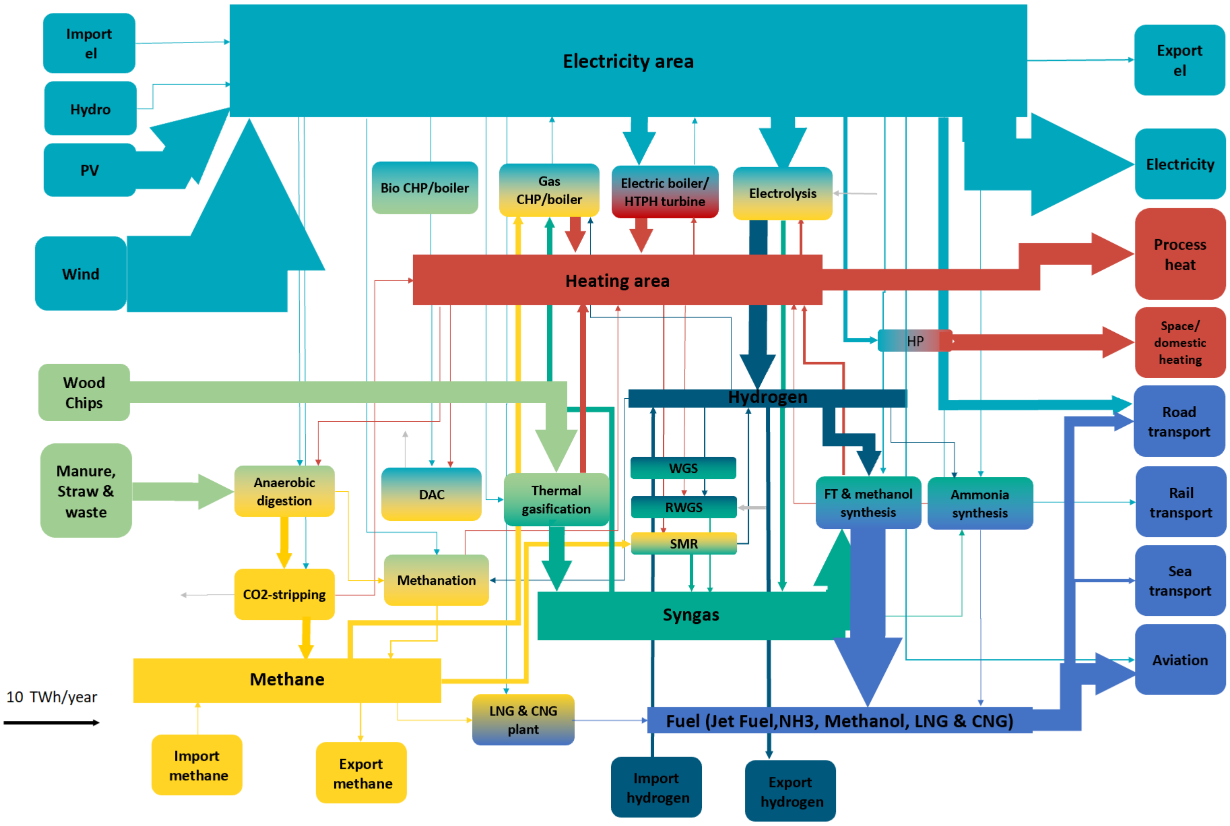


Figure 84: Appendix E: Sankey Diagram showing energy flows in West Europe in the Hydrogen Scenario

E.19 Sankey Diagram of South Europe Hydrogen Scenario

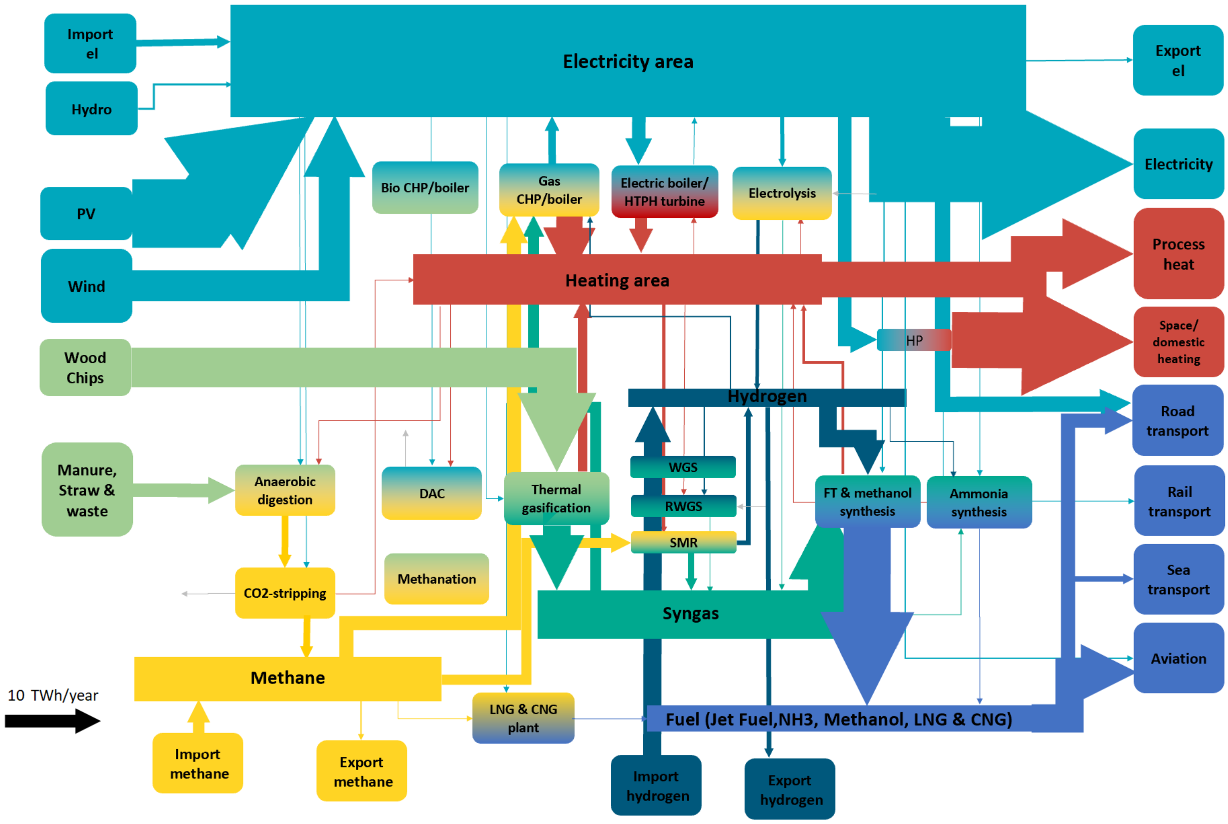


Figure 85: Appendix E: Sankey Diagram showing energy flows in South Europe in the Hydrogen Scenario

E.20 Sankey Diagram of South East Europe Hydrogen Scenario

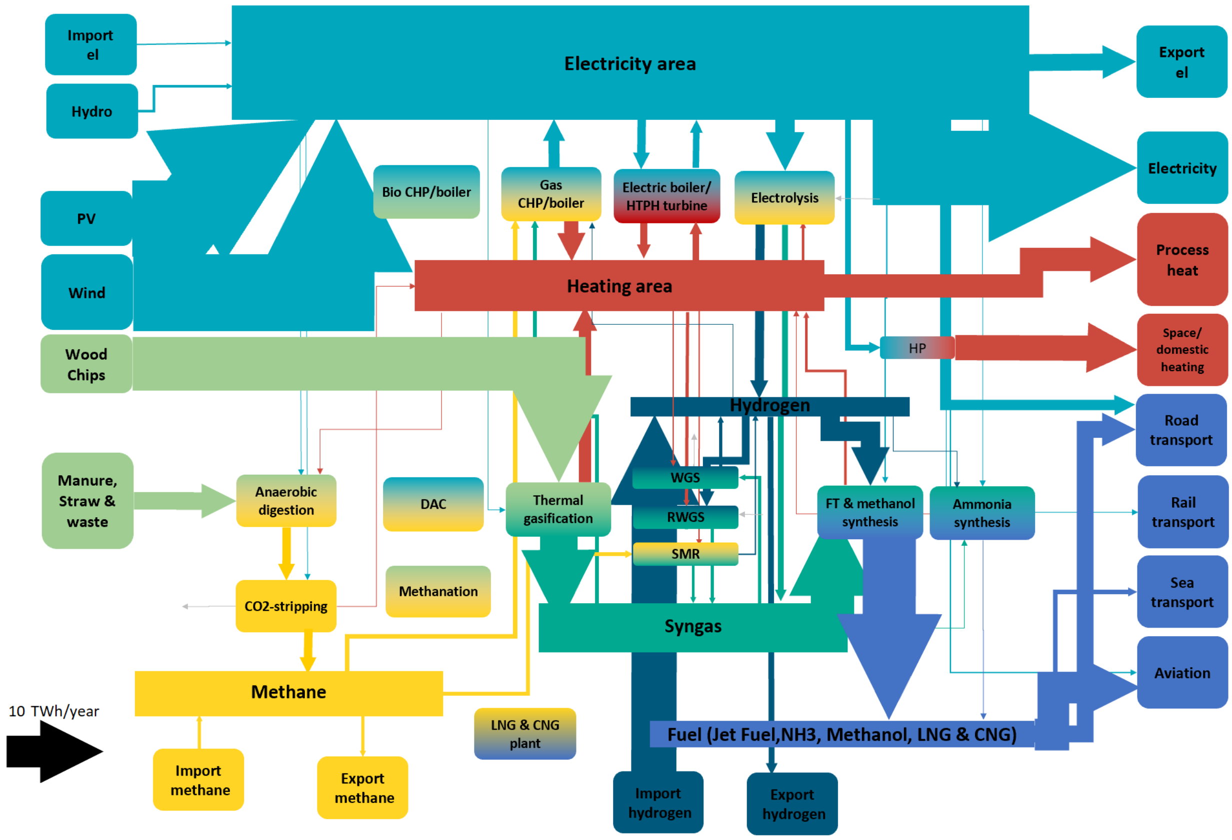


Figure 86: Appendix E: Sankey Diagram showing energy flows in South East Europe in the Hydrogen Scenario