Bachelors' Thesis

Scandinavian Countries' perspectives on low-carbon industry transition

Bachelor Thesis project in Mechanical Engineering

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Abstract

This thesis examines the relationship between industry structures and low-carbon energy transition in the Scandinavian countries. The thesis is sorting out the most carbon intensive industries in Scandinavia and then analyzing the energy mixes the industries use in order to operate. The selected industries the thesis proceeds to analyze were the steel manufacturing industry the cement manufacturing industry and the refining of petroleum products. In order to grasp the energy use and supply of the chosen industries, different reference energy systems (RES) where established for the three different countries, which was the main methodology for this thesis. The RES provides an overview of the energy mixes of the energy supply and demand of the chosen industries. One of the main findings were that most of the emissions in the steel and cement industry occur in the chemical processes, while the largest source of emissions in the refining industry came from the combustion of natural and refinery gas.

The next phase of the thesis provides results regarding new technologies for the industries that allows them to operate without emitting any greenhouse gases (GHG). The thesis argues that the refining industry will be converted into bio refining, making solely bio fuels. Regarding the steel industry it was found that hydrogen could be used as an reducing agent instead of using cok which allowed them to reach zero emissions. For the cement manufacturing industry a plasma technology in combination with carbon capturing and storage would allow the industry to reach zeros emissions. Although this technologies where found to be the most reasonable to utilize in the future, the cost is a huge increase in demand for green electricity. This is shown in a RES diagram which illustrates the energy flows in the energy systems for the studied countries and industries for 2050. The findings shows that the demand for green electricity and bio mass will rapidly increase in 2050. Furthermore, the biggest challenges lies within the expansion of wind power that will provide the new industry technologies with green electricity. Another challenge for the future energy system is the supply of bio mass, which will take the role of fossil fuels in 2050.

Keywords: Decarbonization, Industry, Scandinavia, Wind power, Bio mass, Reference energy system

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Nomenclature

Security of Supply - The capacity that the suppliers have to deliver what has been previously agreed.

Manufacturing Industry - An industry that focuses on the transformation of goods.

Greenhouse Gas (GHG) Emissions - All gases that contribute to global warming.

Total Energy Supply (TES) - The overall supply of energy for all activities on the territory of the country. This includes imports, exports, losses, reclassification, and return flows. Excluding international aviation traffic and marine bunkering outside borders.

Green energy source - energy source that is free from carbon emissions.

Renewable energy source - Energy source that comes from sources that can be naturally replenished.

Carbon Intensity - The share of CO_2 - equivalents in relation to the energy consumed. For example, how much CO_2 - equivalents are being emitted per joule of energy that is consumed.

CO_2 **- Equivalents** - All GHG are compiled and scaled after their global warming potential (GWP) and summarized in unit CO_2e. e.g. The GWP of methane is 25, which means that burning 1 unit of methane is equivalent to burning 25 units of CO_2.

Carbon Border Adjustment Mechanism (CBAM) - A proposal from the European Union suggesting that all carbon-intensive products that are imported to the European Union should be taxed based on how much CO_2 they have emitted prior to entering the area of the union.

Carbon capture and storage (CCS) - A technology to capture CO_2 emissions and storing it in storage sites.

Climate Change - Climate change is the impact of global warming, which results in higher temperatures on earth and its impact on the weather conditions.

Electrification - Electrification is a process of powering by electricity, often replacing a earlier power source like fossil fuels.

European Union (EU) - A economical and political union between 27 European states.

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Introduction

This chapter aims to give background information regarding the thesis project on the topic of Scandinavian countries' net-zero carbon emission industry transitions. It also outlines the objectives and scope of this research.

1.1 Background

With the alarming impacts of climate change, countries need to mobilize efforts to decarbonize their economies. This is clearly acknowledged in the Paris agreement, an international commitment for climate change mitigation and adaptation. According to UNFCCC, "The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016."[1]. It was created to combat the effects of climate change and limit global warming to well below 2°C and ideally below 1.5°C [1].

In 2019, Scandinavian countries, together with other Nordic countries, signed a joint Declaration on Carbon Neutrality. The aim of the declaration was to become carbon neutral in line with COP21 [1] and the Paris Climate Agreement [1]. Nordic Energy Research, a platform for co-operative energy research and policy development under the auspices of the Nordic Council of Ministers, presented several different scenarios namely the Nordic Clean Energy Scenarios [2] with the aim to support this ambitious goal of becoming carbon neutral in 2050.

The COP21 agreement puts pressure on the industry sector to dramatically reduce its CO_2-emissions to reach this aspiring goal. Meanwhile, the industry sector is one of the biggest polluters worldwide after electricity and heat production and transportation, accounting for 19% of the total $C0_2$ emissions

[1] 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change [1]

[3]. Therefore, this is a sector with great potential for improvement in terms of decarbonization. This means that industries will have to be innovative in creating new technologies, improving their business models, introducing effective policies, and so on. A core approach from the Nordic Clean Energy Scenario relies on electrification and the use of decarbonized fuels such as biogas or green hydrogen [2].

The Scandinavian region consists of three countries Sweden, Norway, and Denmark. The region is interesting to study, as they are committed to reaching carbon neutrality by 2050 [2]. These three countries also have strong economies, allowing large green investments to be implemented in the industry sector. Another interesting aspect is that Sweden and Denmark are involved in the European Union (EU), while Norway is not. This can have an impact on trade regulation and political influences. Despite their geographical vicinity, the countries also have important differences in natural resources and economic conditions and structures which leads to different setups in their domestic energy mix.

In terms of energy system setup, Norway is highly reliant on hydro-power which stands for about 90% of their total electricity production [3]. Sweden has a more diverse share of energy resources for electricity production. The largest providers are hydro power, nuclear power, and wind power. In recent years, Sweden has seen a trend towards a more wind-powered energy mix, increasing from 11% in 2019 to 17% in 2020. Denmark generates most of its electricity from wind power, biofuels, and coal. This shows that challenges for electrification and associated solutions may differ between countries, sectors and technologies to meet the climate goals [3].

The industry sectors in Sweden, Norway and Denmark are different to a great extent. Sweden dominates in heavy manufacturing industry, such as car manufacturing and steel production. Norway on the other hand are bigger in oil and gas production and the refining of various petroleum products. They also have business within ocean transport, fishing and aquaculture. In Denmark the biggest industrial sectors is livestock and light industries such as pharmaceutical and other med tech industries. Since the type of industry varies between the countries, different strategies will be needed for Scandinavian countries' energy transition. In addition new industries may be created while old industries may be phased out. As each industry requires different sets or raw materials and energy supply in order to operate, it is crucial to understand how industry structures influence the future changes in the increasingly electrified energy landscape of these countries.

1.2 Aims and Objectives

This thesis aimed to investigate the relationship between industry structures and low-carbon energy transition in the Scandinavian countries. The aim was to provide visual representations of the energy system fo reach of the Scandinavian countries. The visualisation should be for both the energy system for 2020 and for 2050.

The analysis was carried out on the industries with the highest CO_2-emissions, both in terms of what it is now and how it may look in the future. The energy consumption of these industries was also explored to understand the energy mix and the potential to reduce carbon intensity in the energy use in these sectors.

In Norway, the industrial sector is the most energy consuming sector, in Sweden it is the second biggest, and in Denmark it is the third most consuming sector after households and transport [3]. Overall, it is most interesting to investigate the industry sector since it constitutes a majority of the emissions emitted in the Scandinavia. It is therefore the area where significant contributions to climate change mitigation can be made.

In 2020, all of the Scandinavian countries were in the top ten of highest GNP (gross national product) per person in the world [3]. The countries' economic and political stability offers the opportunity to be ambitious and innovative with industrial decarbonization, which can serve as a blueprint for the rest of the world to learn from.

As new technologies are emerging and society is becoming more and more digitalized, the industry sector also changes with potential replacement of existing industrial practises. The aim of this thesis is to understand how the decarbonization of the industry sector affects the energy demand and primary source of supply. The following research questions to be answered are as follows:

1. What are the industries with the highest shares of emissions in the Scandinavian countries and how do they use energy?
    (a) What are the main sources of emissions in these industries? To what extent are they related to energy?
    (b) What are the main energy sources and flows in these industries at present?
2. How can the provision of carbon-free energy be increased in the industries with the highest shares

of emissions in the Scandinavian countries in the future?

(a) What major changes in industrial processes and scales would affect industrial energy use by 2050?

(b) What changes in the energy supply mix would the changes in industrial processes and energy demand introduce by 2050?

1.3 Scope

This thesis focused on the the impacts of the industrial decarbonization to the energy system composition. It therefore, did not include the household, service, transport and agricultural sectors. In addition, the focal point of the research was on the most carbon-intensive sectors in each country's industry. The methodology used analyzed the energy flows rather than the material flows, industries with large emissions that are not related to energy were excluded as well.

The data that provided the foundation of the thesis is from 2020 because there was a lot of research and well documented data from that year compared to 2022. The point of comparison in regards to future scaling was 2050. The reason that 2050 was used is because all these countries set climate neutrality goals by 2050 and most scenarios were built around this year [2].

2

Most Carbon Intensive Industries in Scandinavia

The first phase of the thesis was to acquire knowledge in which of the industries within Scandinavia that where the most carbon intensive. Various data bases for the different countries where utilized to understand the carbon intensity of each industries. In order to understand the relationship between industry structures and a low carbon energy transition, the energy mixes of the different industrial sectors were mapped out. Furthermore, this subsection defines which industries the thesis will focus on with respect to the scope in section 1.3.

2.1 Energy Consumption in Norway

In 2020, Norway consumed 248 TWh of energy where 52 TWh was consumed by the transportation sector and 83 TWh by the industry sector. The rest of the energy is consumed by the households and by other commercial and public activities such as lighting or various community services [4].

2.1.1 The Manufacturing Industry

The most energy intensive sector in 2020 was "Manufacturing and mining industry" according to the Norwegian statistics [4]. The Manufacturing part contributes with about 98.5 % of the energy use, see Table 2.1.

Table 2.1: Energy use by sector

Sector	Energy use $[TWh]$	percentage
Manufacturing	78.5	98.5
Mining	1.2	1.5
Total energy use	79.7	100

The various manufacturing industries can be divided into further sub-sectors (The categorization done by the Norwegian Statistisk Sentralbyrå (SSB) is used).

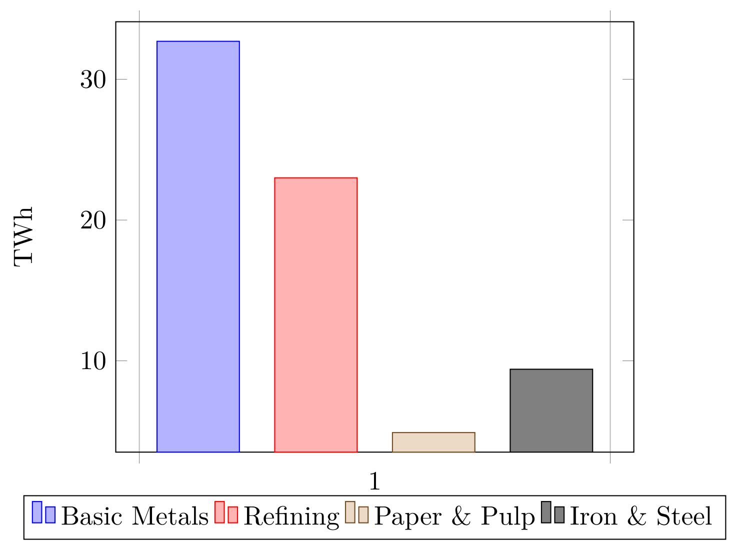

Figure 2.1: Energy consumption by sub-sector in manufacturing industry in Norway 2020

Figure 2.1, shows two sub-sectors that stands out in terms of energy consumption. The largest is the "Basic metals" industry which accounts for about 39.6 % of the total energy consumption within the industries in Norway. The second most energy-consuming industry sub-sector is the industry behind refined petroleum, chemicals and pharmaceutical products, which accounts for about 32 %. These two industries together are responsible for more than 70 % of the total energy consumption within the industrial sector in Norway and it could therefore be concluded that the two constitute Norway's most energy-intensive industries[5]

2.1.2 Basic Metals

According to the Norwegian Statistik Sentralbyrå the manufacturing of basic metals consumed 32.71 TWh (2020). The Basic metals are grouped into sub-sectors according to the SSB, where the biggest consumer was "Manufacture of basic precious and non-ferrous metals" with 22.74 TWh which is about 69.5 % of the total manufacturing of the basic metals energy consumption. For instance non-ferrous metals could be aluminium, copper or zinc etc [6].

After further research it was found that aluminium constitutes the largest production of all non-ferrous metals [7]. According to the Norwegian Government's website, Norway has seven production plants around the country, with the largest located in Sunndal and Årdal [7]. They export about 80-90 % of their production, making them the largest exporter of aluminium in western Europe.

2.1.3 Refined petroleum-, chemical,- and pharmaceutical products (RPCHP)

The sub-sector "RPCHP" is the second most energy-intensive industry and consumed about 34 % of the manufacturing industry [5]. Further, the sub-sector could be divided into two branches, where one constitutes the manufacturing of basic chemicals and the other the manufacturing of refined petroleum products. The basic chemicals industry was by far the largest in terms of energy consumption.

2.1.4 GHG Emissions in Norway

SSB states that all the industries in Norway emit about 61 million tons of CO2-equivalents (2020). The biggest emitting industrial sectors according to SBB are presented in Table 2.2.

Table 2.2: GHG emissions in Norway

Industry	Million tons of CO2-equivalents
Transport	21.44
Oil and gas extraction	14.66
Manufacturing	11.83

Even though the transport sector is the largest emitter, the thesis did not proceed with this sub-sector, because the thesis did not aim to focus on the transport sector, see section 1.2. After further analysing the data presented in Table 2.2, "Oil and gas extraction" is the second largest. Which is mainly due to their inefficient energy use. In Norway the oil rigs are powered by gas turbines which in most cases burn natural gas [8], this makes their electricity production very carbon intensive. Even though the manufacturing sector is very large in terms of energy consumption, their GHG emissions are not that significant. The refining industry emitted 4,73 million tons of CO2-equivalents and the manufacturing of basic metals emitted 4.2 millions. Since these three industries are the most carbon intensive they will be analysed more in detail in the RES - diagram. When analysing the industry in more detail it enables for answers to the research question 1b.

2.2 Energy Consumption in Sweden

According to Energimyndigheten, Sweden's national energy institute and the main institute for covering energy statistics, Sweden's industry is the second largest sector regarding energy consumption and stands for about 38 % of Sweden's total energy consumption[9].

2.2.1 The Manufacturing Industry

When analysing the manufacturing industry in Sweden, the paper and pulp industry stands out in terms of energy consumption. It consumes by far the most energy followed by the basic metals industry, see Figure 2.2.

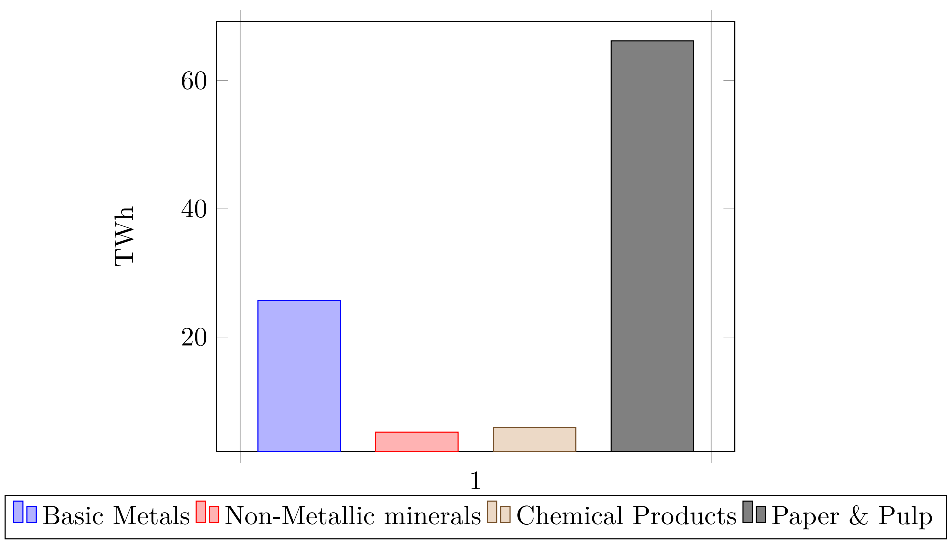

Figure 2.2: Energy consumption by sub-sector in manufacturing industry in Sweden 2020

2.2.2 GHG Emissions Sweden

When analysing the industries for the most carbon intensive sub-sectors in Sweden it differs quite significantly from the graph showing the energy consumption, see Figure 2.2.

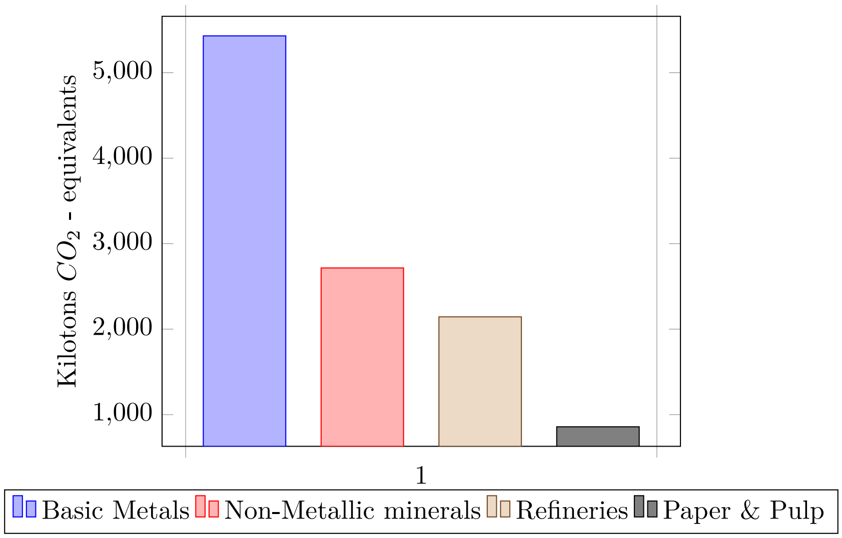

Figure 2.3: Emissions by sub-sector in manufacturing industry in Sweden

The by far most carbon intensive industry is the Basic Metals industry, followed by the non-metallic industry and the refineries, see Figure 2.3. The emissions in the non metallic industry come mostly from the cement production and this will be one of the industries that the thesis will proceed with. Furthermore, the refineries are also a big emitter and this is also one of the industries the thesis will continue to analyse. It is note worthy that even if the paper & pulp manufacturing is very energy consuming it is not particularly carbon intensive.

2.3 Energy Consumption in Denmark

In Denmark, the total energy consumption in the manufacturing industry went up to 26.6 TWh in 2020, which was about 15 % of the total energy consumption of 2020 [10, 11]. The distribution of energy consumption in the manufacturing industry is shown in Figure 2.4, where the most energy intensive sub-sectors are non-metallic minerals, livestock, oil refineries and mining and quarrying. In non-metallic minerals, the manufacturing of concrete is included, which is where about 80% of their energy consumption happens [10]. It was therefore more interesting to look at concrete alone.

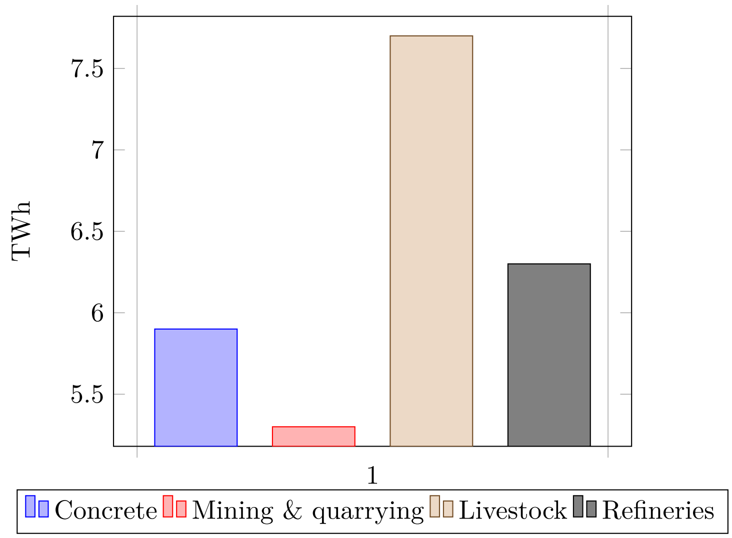

Figure 2.4: Energy consumption by sub-sector in manufacturing industry in Denmark

2.3.1 GHG-emissions in Denmark

Regarding the emissions from these sub-sectors, the actual GHG emissions are shown in Figure 2.5. The chosen industries are those who emitted the most CO_2-equivalents. The data provided in the bar chart is extracted from the Danish statics bureau [10].

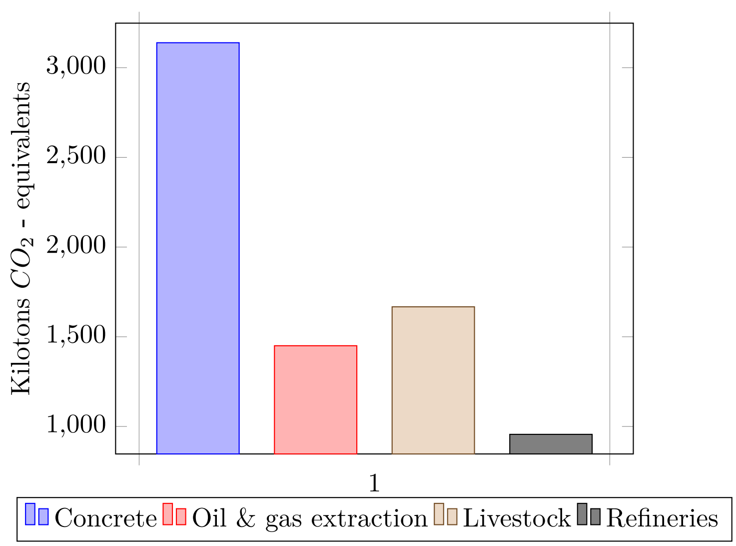

Figure 2.5: Emissions by sub-sector in manufacturing industry in Denmark

The by far heaviest emitter in Denmark is the manufacturing of concrete followed by the livestock industry, see Figure 2.5. The livestock industry includes milk and dairy production, meat production, egg production and also the production of fur. The term livestock also includes all the activities related to livestock [10]. Even though the livestock industry is one of the heaviest carbon emitters in the country the thesis did not proceed with the industry. This is because it is very hard to define since the structure is very decentralised and the chosen methodology is not suited for this type of industry. Hence the sub-sector was excluded from the thesis and studied industries for Denmark was refineries and concrete.

2.4 Industries to Proceed with

The thesis focused on the most carbon intensive sub-sectors in the Scandinavian countries and how the emissions are related to energy consumption. Therefore, even if the livestock industry is one of the biggest GHG-emitters in Denmark, it will not be analysed in the RES-diagrams because many of its emissions are not related to energy consumption. In some countries, agriculture and certain types of transportation is included in the definitions of industry sub-sectors. As it was defined in the scope of this thesis that the focus would be on manufacturing industries, agriculture and transportation will not be included either.

In conclusion the biggest emitters, with regards to the scope, are in Norway the manufacturing of non-ferrous metals, oil and gas extraction, the RPCHP industry and the oil refineries. In Sweden, it was the steel manufacturing, oil refineries and cement production. In Denmark, the chosen sub-sector industries were the cement production and oil refineries. It was in the interest of the thesis to further examine the carbon intensity in the energy mixes for all of these industries. Furthermore, all these industries are well suited to the methodology and adapted to in Results, see chapter 4.1.

3

Methodology

This section explains the method, tools and processes that were used for answering the research questions presented in the section 1.2 Aims and Objectives.

3.1 Reference Energy System

In order to understand the energy sources and flows in the main carbon-intensive industries at present and the associated sources of energy-related emissions (research question 1) a mapping of the energy flows within the industries was conducted. To do so, the thesis used a Reference Energy System (RES) as the primary methodology. The RES is a graphical network representation of how energy flows from primary energy supply to final energy consumption. To compile the RES diagram, data from the most recent year for which data is available will be used to provide the representation of the current studied energy system. The RES is therefore a static representation, showing the energy system over a single year. The purpose of the RES is to create a comprehensive overview of how energy is supplied and consumed within the boundaries of a predetermined system [12], in this thesis, it will be done on Sweden, Norway and Denmark. The energy in the system includes both heat that is supplied to the district heating network and electricity which is supplied to the grid, for some countries a gas grid will also be added in the representation.

The system is made up of "energy consumers", "energy conversion technologies", "energy carriers", and "energy sources". The energy consumers are located at the right hand side of the diagram and illustrate which economic sectors that are consuming the energy and how much each sector is consuming [12]. For instance, energy consumers could be industries, transportation or households. To provide the consumers with energy it has to be transported in different qualities, via energy carriers. Energy carriers could be fuels such as petroleum products, biomass or combustible waste products, but it could also take other forms such as steam, hot water or electricity. Energy sources are providing the system with energy carriers. The energy sources are characterised by costs, price and accessibility [12]. For instance, the source of biomass is the forest and the source of petroleum products and coal is the international markets. To convert the energy sources into desirable energy carriers different kinds of energy technologies are utilised. For instance potential energy from water (energy source) is converted into electricity (energy carrier) by a turbine (energy technology) and finally provided to the the energy consumers. For a visualization see Figure 3.1

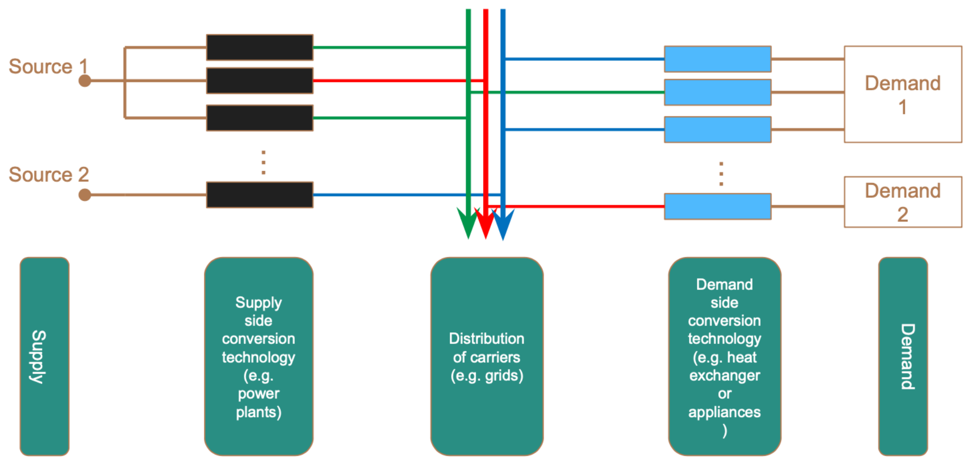

Figure 3.1: Outline of a RES Diagram

3.1.1 Establishing RES-diagrams

Before designing the RES-diagram the actual layout was carefully thought out. The energy conversion technologies were positioned on the left side, as described in section 3.1. For all three countries, the refinery was positioned to the left in the diagram, making it a conversion technology. One could argue that the refinery is an industry and should be placed at the consuming side. The reason for the placement is due to its production of various petroleum products that are used by other industries and also the transportation sector. The refineries also convert one form of energy into another, which could also be used as an argument for the placement. Lastly, it was also more practical to position the refineries at the left side, freeing up more space for the arrows representing the energy flows. To minimise the amount of arrows only the net of the produced energy were illustrated in the diagram. If, for instance a power plant consumes 5 TWh and produce 7, only 2 TWh will be illustrated in the diagram. Another assumption made in order to minimise the complexity of the diagram and make it more comprehensible were to combine the different combined heat and power plants (CHP) into one unit. The same goes for the district heating plants (DHP). The assumptions were made with regards to the objectives of the report, that it solely intends to focus on the industry sector and not on the converting technologies, see section 1.2. The sources used for creating the RES-diagrams were for Norway *Statistics Norway* [13], the *Swedish Energy Agency* [9] for Swedens RES and *The Danish Energy Agency* together with *Statistics Denmark* [11, 10] for the Danish RES-diagram.

The consuming side of the RES-diagram (the right side) was divided into households, transportation, industry and non energy use. The household classification also includes public and commercial activities and also other activities. In the others sub-sectors was a number of different sub-sectors combined, for example was sub-sectors such as fishing, forestry and agriculture were included. These sectors were not of interest, hence the rough classification. The same could be applied for the transportation classification, which also included various sub sectors that were irrelevant for the thesis.

In order to gain appropriate data for the RES-diagrams, energy balances for 2020 over the different countries were used. The energy balances highlighted how much energy that was produced and consumed within the specific country and year. The difference between the produced and consumed energy was the amount that were exported, used for bunkering or the stock changes. For instance a lot of petroleum products could be produced one year but stored in large tanks and not consumed the same year. The energy balance also covered data over the different transformation processes, such as heat and power plants. Where different energy types such as bio fuels, natural gas or coal where converted to, for instance, electricity and heat for the district heating system. The level of detail regarding the statistics could be decided in advanced which reduced the complexity by combining different energy types. For instance a more detailed view over certain oil products could be obtained when investigating refineries. Since different databases uses different classifications regarding industries and energy types it was decided to only use one database per country. This assumption was made in order to achieve an as reliable result as possible and reduce the number of assumptions and other error factors, such as different classifications for different data sources.

The numbers constituting the RES-diagram were documented in an excel spread sheet. It was important that the amount of energy, both consumed and produced, matched. Hence balancing calculations were performed in the excel sheet to keep track of how fuels entered and left the system. Since petroleum products could be produced but not consumed within that same year the energy balance would never add up. The same issue could be applied for bunkering of various fuels to large ships. The amount of produced fuel would never be the same as the amount of consumed and net exported fuel, therefore the stock change also had to be taken into account when checking the calculations in excel. To obtain the correct stock change, export and bunkering the difference between the total supplied energy of each type was subtracted form the total amount of consumed energy by each type. This difference represented the combined export, bunkering and stock change of each energy type. This is indicated with arrows in the bottom left corner leaving the energy system. This is mainly applicable for diesel, fuel oil and other energy products for non energy consumption.

3.1.2 Statistical Difference

The used databases all had a row called "statistical difference", which aimed to present the error between the measured numbers in reality and the ideal scenario. If the measured statistical numbers where ideal the sum of the supplied energy would be equal to the sum of the consumed energy. To represent the statistical error, the total energy supply are added together with the energy consumed in transformation process. Then the sum of the distribution losses and the the total consumption is subtracted. When analysing the statistical differences for each country it was concluded that it was very small and only responsible for a few percentage points. Although the statistical difference overall were quit moderate it could be rather large especially for various oil products. This could be due to the reclassification of different flows when refining crude oil to other petroleum products. Therefore, the energy source side regarding the petroleum products are taking the statistical difference into account in order to make the flows add up. Since the difference is so small when it comes electricity and other energy types and the RES only uses three value figures the statistical difference will not interfere with the actual values in the diagram.

the statistical difference could be larger This row showed how much the statistics differed from reality. In an ideal scenario the sum of total supply, the losses in the transformation processes, the energy industries own use, the distribution losses and the the final consumption should equal to zero. For all energy products the statistical difference is only 27 GWh which is very small in comparison to the total energy supply for Norway Which is about 324 TWh. The statistical difference for biofuel, electricity, district heating and coal products were all under one TWh and was therefore not an issue, when creating the diagram. The problem were mainly for natural gas which had a statistical difference of -9,8 TWh, this could be due to losses that were hard to identify and other reasons. Because of this the natural energy balance for natural gas did not add up to zero as it would have done in an ideal scenario. The oil products also had a rather large statistical difference of 9,3 TWh, thud could be due to complexity of the refining process. After further analysis it could be determined that the statistical difference relative the actual energy flows were quite small. Norway are exporting 1 140 TWh of natural gas and 865 TWh of crude oil and also other refined petroleum products. When taking these numbers into account the statistical difference in relative terms are quite small.

3.2 Data Management

In order to establish the RES-diagram it was of outmost importance to obtain highly reliant and up to date statistic over the energy consumption and supply. To streamline the terms and reduce the complexity only one source of statistic was utilised for each country. The data gathered for the RES - diagrams was obtained from each of the countries statistical bureau.

3.3 Tools and resources

To visualise the energy systems graphically a program called "diagrams.net" was used. "diagrams.net" is a website that can be used to do different types of illustrations, and has, therefore, pre-done arrows, text-boxes, as well as different kinds of geometries and charts.

Microsoft Excel was used as the main software for data processing and visualisation of pie charts showing, for instance, the energy distribution of different energy types in the countries. It were also used for the data handling and the calculations needed for the RES modelling. Excel was chosen because of its versatility and high level of user-friendliness. For instance, the excel sheets were shared between the researchers which facilitated the coordination in the progress of data management. It is also a very good program in terms of processing large amounts of data and implementing basic calculations between cells which was adequate for the thesis.

4

Results

4.1 2020 RES-diagrams

This chapter attempts to answer research question 1 by providing the 2020 RES-diagrams for each country. The industries that have the potential to decarbonize are identified.

4.1.1 Norway 2020

The highlighted industries in Norway are the non-ferrous metals, manufacturing of chemical and petrochemical products, extraction of crude oil and gas and the oil refineries. As discussed in chapter 2 the extraction of crude oil and natural gas were together responsible for the largest CO_2-emissions in 2020. When analyzing the RES-diagram for Norway, it can be inferred that these large emissions were due to the vast amounts of natural gas that was combusted in the extraction process, 48.6 TWh. Gas oil is also being used, mostly to get supplies from ships to the rigs, which also contributes to the emissions. The industry also uses a considerable amount of electricity, but since the electricity is mostly provided by wind- and hydro power this is does not generate the same amount of CO_2-emissions. In order for the process to be more sustainable, the rigs have to find other ways of operating.

As electricity in Scandinavia mostly comes from green sources, such as wind and hydro power, industries that use mainly electricity have already been decarbonized. This becomes clear in the RES-diagram, Figure 4.1, which shows that the two biggest electricity suppliers in Norway, hydro power with 142 TWh and wind with 9.9 TWh, stands for almost all of the electricity production. There are small producers of electricity that are not green, such as the CHP and geothermal energy transformation technologies that uses small amounts of coal and oil products. They produce 2.7 TWh of electricity, which in comparison to the amounts of electricity produced from hydro power and wind power can be seen as negligible. Industries that mostly uses electricity in Norway can therefore be seen as having a low potential for decarbonization. The manufacturing of non-ferrous metals is the most energy intensive industry with a total energy use of 22,7 TWh, where electricity stands for 21.9 TWh. Since the electricity production is almost completely green, the non-ferrous metals industry is already relatively clean. Industries which use vast amounts of fossil fuels, such as the the production of crude oil and natural gas have a higher potential for decarbonization, since they are so carbon intensive.

Refineries is another sub-sector that has potential to be decarbonized, mainly due to its use of crude oil. Norway uses extensive amounts of crude oil among the studied countries, at 141 TWh. A challenge in decarbonizing the refineries is that the products that they produce are provided to other sectors, such as transport and industry. As can be seen Figure 4.1, the transportation sector is vastly dependent on the diesel, kerosene and gas oil provided by the refinery, as they stand for almost 70% of the energy consumption. If for example the refineries would revamp to producing other fuels that are greener, then the transportation sector would have to adjust to be able utilize these. This also goes for the chemical and petrochemical sub-sector, as parts of their energy comes from oil products and LPG from the refineries. In chapter 4.2, the thesis further analyses this industry and present solutions to how this industry can operate in a more sustainable way in line with the goal of carbon neutrality for 2050.

When it comes to the export side it becomes clear that Norway is a big exporter of energy. The crude and gas production stands for a clear the majority of the energy export with a gas export of 1087 TWh, and crude net export of 865 TWh. When comparing to what the oil refineries exports, 6.9 TWh of fuel oil, 5.2 TWh of diesel, the model also shows that that almost all of Norway's exports in terms of energy comes from the crude & gas production.

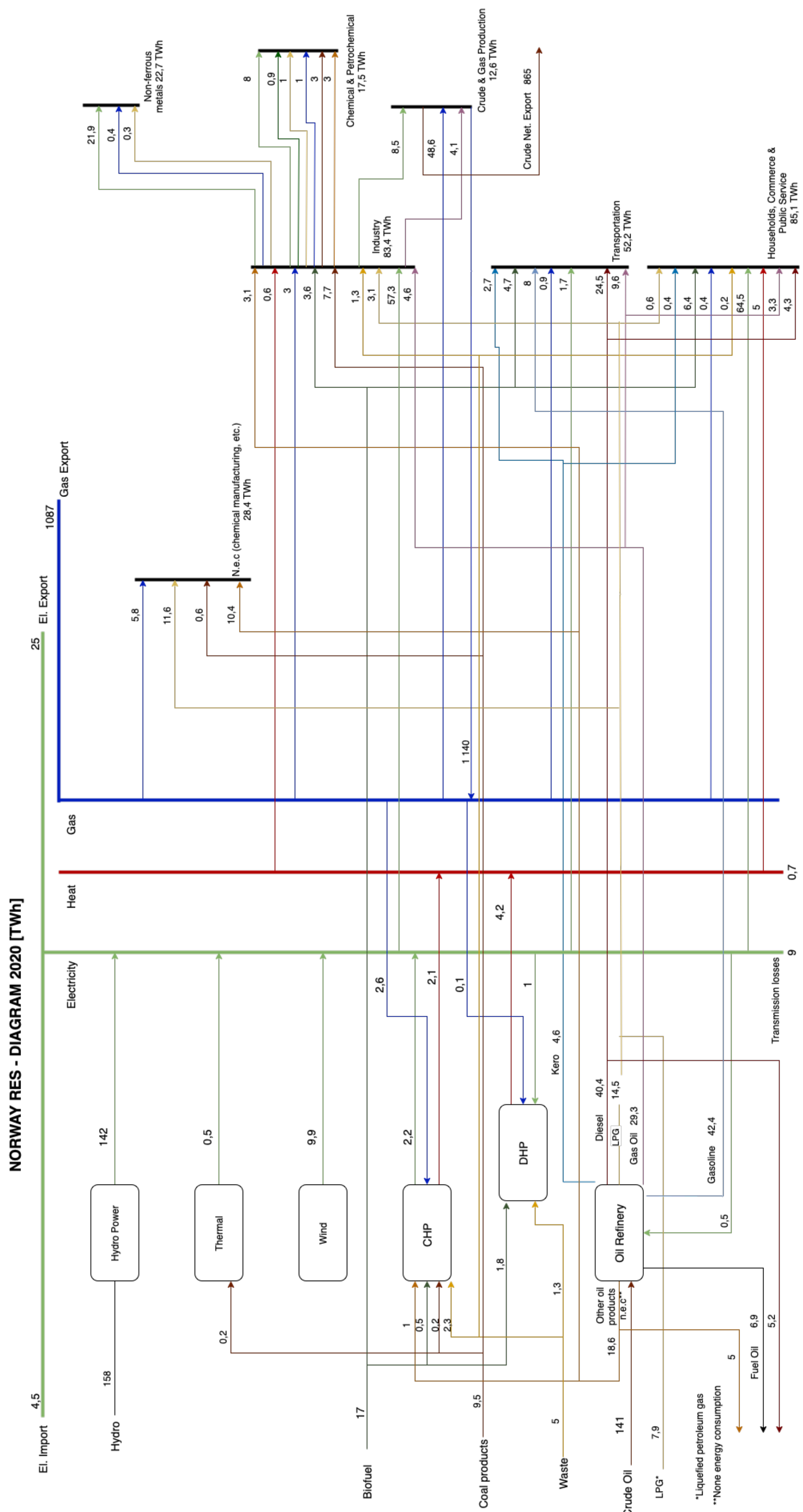

Figure 4.1: RES-Diagram over Norway 2020

4.1.2 Sweden 2020

After analyzing the RES-diagram, several observations could be drawn regarding the energy consumption and production. For Sweden the three highlighted industry sub-sectors are refineries, cement production and the iron and steel manufacturing, which all are heavily dependent on fossil fuels in order to operate. The iron and steel industry uses 7.6 TWh of coal and coke, which is illustrated by the brown arrows in the RES diagram see Figure 4.2. The production of non-metallic minerals constitutes the major part of cement production as well as emissions. [14]. The nonmetallic mineral industry utilises around 3.5 TWh of fossil fuels. As the RES diagram shows, are a wide variety of energy carriers used in this industry, where more than 70% are fossil fuels, such as coal products, petroleum products, and different fossil gases. This makes it an industry where electrification and other breakthroughs could have a big impact. Sweden imports and refines large amounts of crude oil, 198.8 TWh, which makes it challenging to meet the carbon neutrality targets. The majority of petroleum products are consumed in the transport sector or exported. However, considering the Swedish goal of net zero emissions by 2045 within the transport sector, the emissions will have to be cut back soon [15].

A difference from the other studied countries is the use of nuclear power for the production of electricity, about 47.3 TWh, which is an emission-free energy source but not a renewable one. The vast majority of Sweden's electricity production comes from clean energy sources. Over 92% comes from nuclear, wind power, solar power or hydro-power. This implies that the potential for electrification in industries where electricity could replace fossil fuels is immense. This can be seen within the steel industry in Sweden which is making the transition to electrify its production, this can be read more about in the processes section in chapter 4.2. The potential for carbon emission mitigation for already electrified industries is therefore quite limited since the electricity used in these industries are clean.

Another notable result in Sweden's RES diagram is its considerable use of biofuel which is used for the production of heat and electricity and in the transportation sector. Since Sweden has large areas of forest, there is a large potential to valorize domestic forest resources.

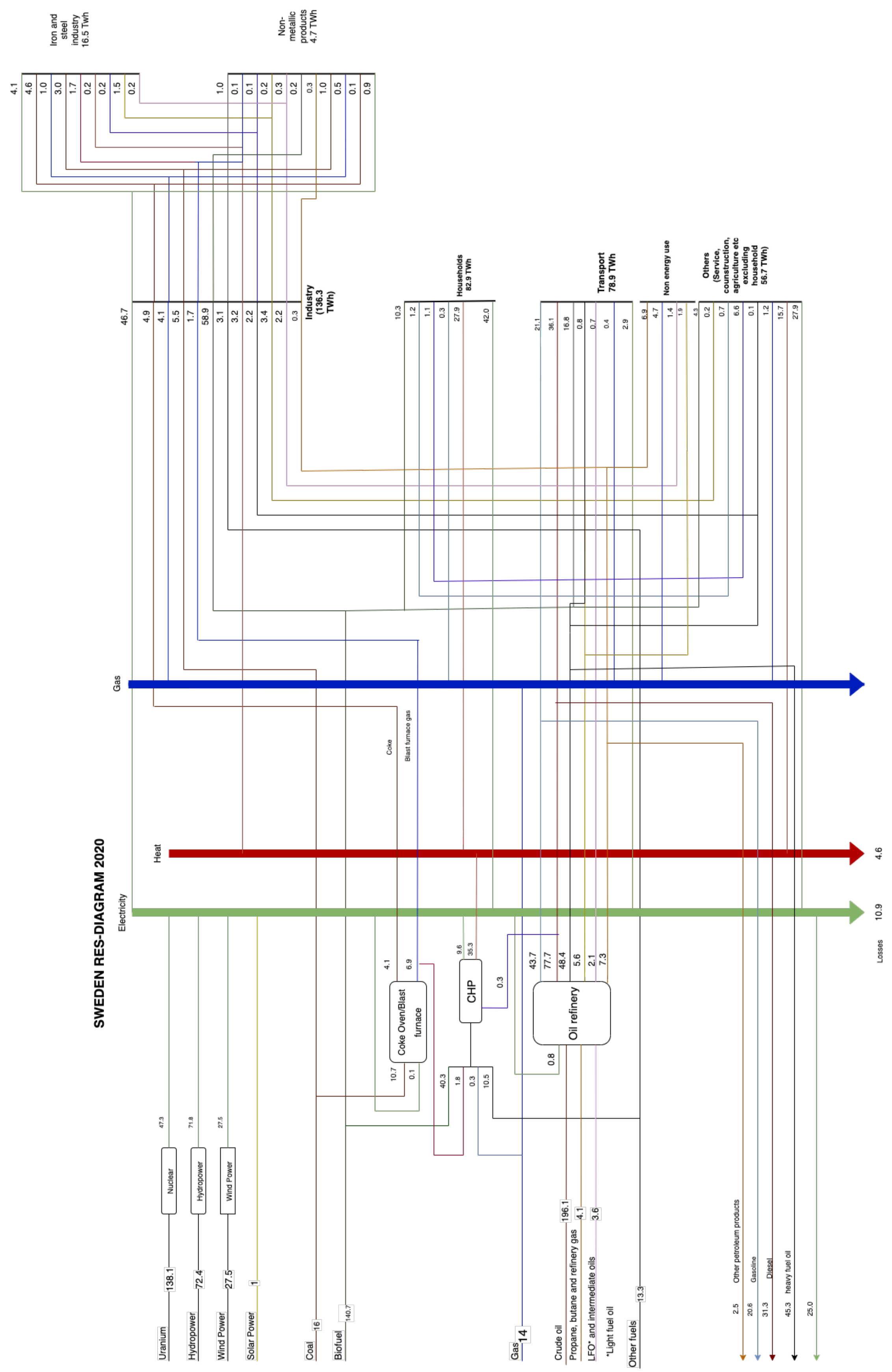

Figure 4.2: RES-Diagram over Sweden 2020

4.1.3 Denmark 2020

Denmark is the country with the smallest industry among the three studied countries, which could be seen in the RES-diagram, see Figure 4.3. The industry sub-sector only uses 26.6 TWh, which is very small in comparison to Sweden and Norway. Furthermore, two industries are highlighted, the manufacturing of non-metallic minerals and the oil refineries. Since the thesis aims to investigate the industry sectors, the largest potential for decarbonization lies within the non-metallic minerals industry and more specifically the manufacturing of concrete. When looking at the emissions, the manufacturing of concrete is responsible for almost all the emissions in this sub sector [10]. As seen in Figure 4.3, the cement production uses mostly petroleum coke (an oil product) and coal, which is used to heat the rotary kilns. It also uses some electricity, but that is not used in the carbon intensive process of heating the kilns. Apart from the emissions from CO_2 being released from the limestone, the majority of emissions come from heating the limestone and turning it into cement clinker [16].

A difference from the other studied countries is that Denmark's electricity production is not as green. As can be seen in Figure 4.3, Denmark imports quite a lot of electricity, 18.6 TWh, and produces 16 TWh from wind turbines. A difference from the other countries is that Denmark also uses solar power, even if it is a rather small amount at 2 TWh. Another difference from the other studied countries is that the electricity production is not as green. Some of the electricity production comes from the combined heat and power plants (CHP), which is powered by 8 TWh of coal and a variety of oil products. Here Denmark has ha great potential to decarbonize. Another aspect of the electricity in Denmark is that there is no guarantee that the imported electricity is green.

It is also worth noting that the oil refinery is the smallest amongst the three studied countries and only has 98 TWh of crude oil as input. As previously mentioned in section 4.1.1, revamping the refineries influences the transportation sector. Another thing that stands out is the conversion technology called autoproducers. The autoproducers could be various industries or private actors producing their own electricity and/or heat for private use and providing the district heating network or the grid with surplus energy. The total energy consumption is also significantly smaller then the consumption in Sweden and Norway, where as Denmark's consumption is only 152.8 TWh.

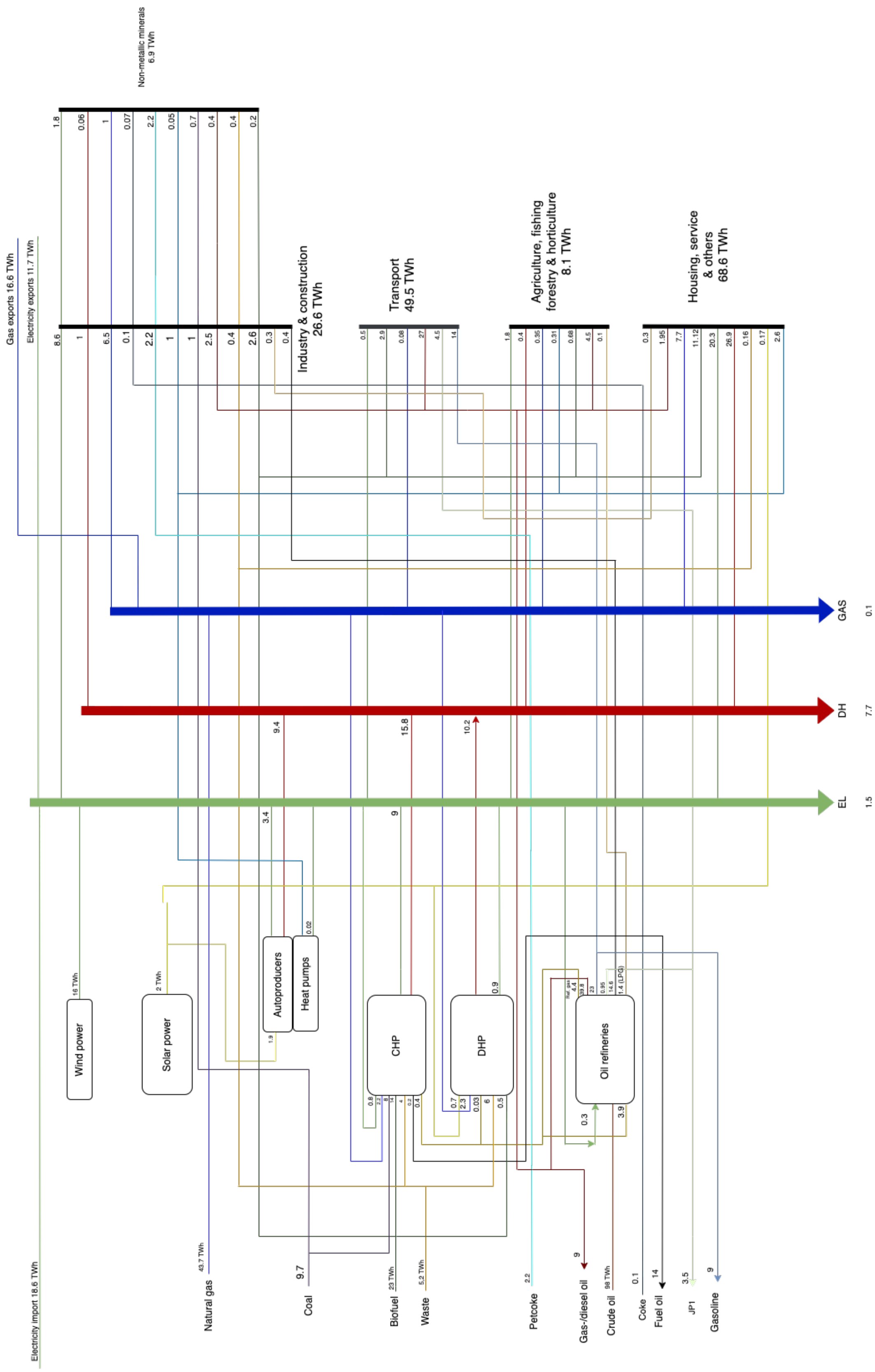

Figure 4.3: RES-Diagram over Denmark 2020

4.2 Processes for Selected Industries

This section attempts to answer research question 2(a) by describing the industrial processes for the selected industries currently and the existing options for changes in the processes in order to decarbonize. The industries are the refining industry, the manufacturing of steel and the manufacturing of concrete.

4.2.1 Steel Manufacturing

In Sweden there are two ways to produce steel, from crude iron (from iron-ore) and from scrap-iron. Crude steel from crude iron is two thirds of the crude steel production in Sweden and is produced in Sweden´s two blast furnaces.[17]

Today is the steel made out of primly iron and about 0.002 to 2.1 weight percentage of carbon, depending on what kind of material properties are wanted. This process is done in blast furnaces with a temperature around 1700 kelvin. The fuel that is used as both heat source and reductant is coke. During the process is lump coke used directly in to the blast furnace and nut coke is mixed with the iron in form of ether pellets, lump or sinter. The energy that is necessary to be able to melt the iron ore are therefore mainly from the coke see Figure 4.4. The CO_2 emissions from using coke as a reducing agent is very extensive [17].

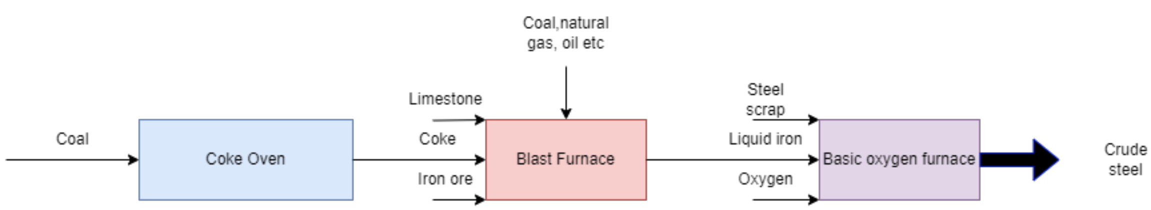

Figure 4.4: Illustration of steel- making process

The sustainable transition of the steel and iron industry center around using coke as a reducing agent. The Swedish parliament has together with Vattenfall, SSAB and LKAB a shared goal of transforming Sweden's most carbon intensive industry into fossil-free steel production. As a result, HYBRIT (Hydrogen Breakthrough Ironmaking Technology) Development AB was founded to revolutionize the steel and iron industry from the current blast furnace production to hydrogen-based production. When coal is removed as a reducing agent, and hydrogen is used instead, the emissions from CO2 will be replaced by steam. The change to hydrogen-based steel and iron production still has some problems in terms of being energy-and cost efficient. The executive vice president and chief technology officer of SSAB, Martin Pei has for example said, "“The biggest challenge that SSAB faces in this case [hydrogen-based direct reduction] is the current blast furnace process. The blast furnace process has been working for a very long time. It is very stable and very energy efficient. It stands out and it works around the clock for the whole year's production. Finding a method that can replace it, that can make iron and steel equally efficiently, and as stably as we have today, is the biggest challenge."". [17] Despite the challenges hydrogen-based reduction has, there is a strong belief in Swedish institutes, companies, and other actors that hydrogen technology is the preferable technology to use in the future, due to the reduction of carbon dioxide. Implementing Hybrit technology could lead to a reduction of carbon dioxide from 1600 kg per ton of steel to 25 kg per ton. In addition, the geographical location of steel plants in Northern Sweden allows convenient grid connection to renewable electricity from hydro and wind power as well as access to biomass resources used in the blast furnace.

In 2017 was a study made on the prefeasibility of Hybrit, and it showed that hydrogen-based use in steel and iron production in northern Sweden is both viable and potentially cost effective when it comes to the carbon dioxide market and electricity princesses in the future. According to Hybrit's own website around 55 TWh of electricity will be required to satisfy the demand of 2050 to produce fossil-free steel and iron.[18] For a visualisation of the process see Figure 4.5.

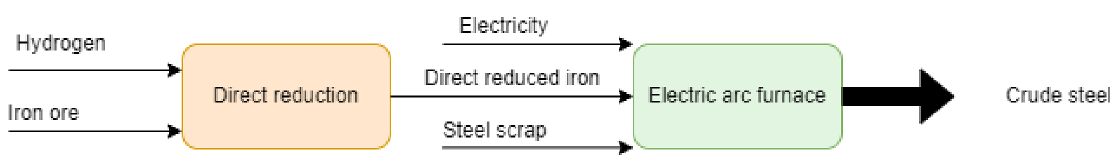

Figure 4.5: Illustration of potential steel-making process 2050

4.2.2 Cement manufacturing

Cement is a main ingredient in the production of concrete since it is what binds the product [19]. The biggest source of emissions in the manufacturing of cement is the calcining process, which is when the limestone is heated to create cement clinker. This clinker is later grounded and blended with other products to create cement see Figure 4.6 [19]. The majority of the emissions comes from the pre-calcining process, which is when the limestone is heated to 900°C to generate a chemical reaction that separates the CO_2 from the stone, which is then emitted into the air [16]. The rest of the emissions come from the fossil fuels used to heat the rotary kilns to create the clinker [2]. The ovens need to be heated to about 1450°C and as of now, the heating fuels used are mostly, coal, coke and oil products, such as petroleum coke, see chapter 4.1.

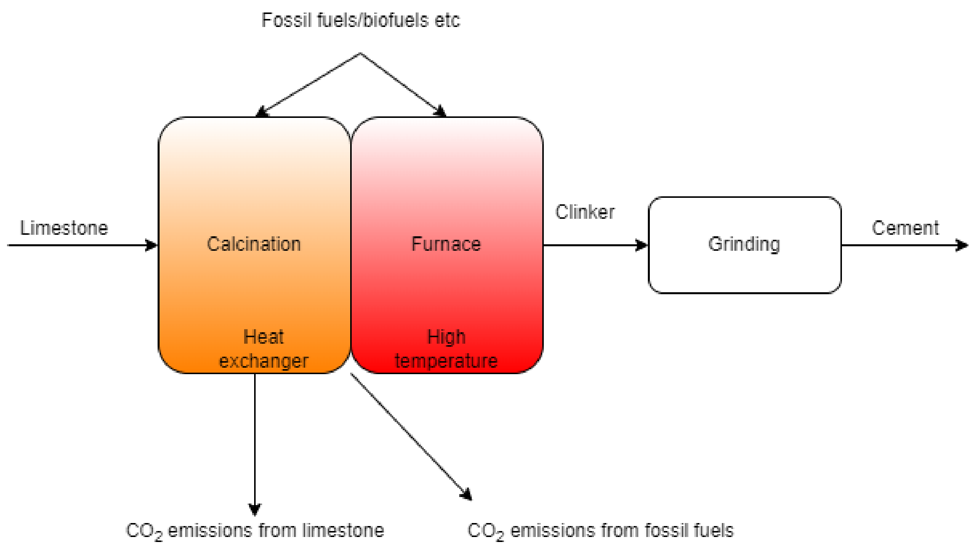

Figure 4.6: Simplification of cement- making process

4.2.2.1 Cement production in 2050

Sweden's government together with Sweden's only cement producer Cementa AB took forth a roadmap on how to solve the challenges with cement production in Sweden in 2018 [20].

- Energy optimization.
- Phasing out fossil fuels by increasing the amount of bio fuels.
- The development of new cement types with a lower carbon-footprint.
- Research in increasing the carbon dioxide uptake of the existing concrete structures.
- Carbon capture and storage/utilization (CCS/CCU)

It is worth noting that emissions in cement manufacturing can be abated by replacing cement clinker with other materials, such as fly ash and gypsum [21], but since the thesis focuses on the emissions related to energy use, alternative solutions like replacing materials was not looked at.

4.2.2.2 Increase efficiency

Increasing efficiency is widely focused on the use of wet versus dry-process kilns. The dry kilns are more energy efficient because of the low moisture content, leading to a lesser need for energy in evaporating water from the raw material [19].

4.2.2.3 Switching to alternative fuels

As of now, about 70% of the fuels used in the kilns are coal, oil and natural gas 24% and bio fuels and waste 5% [21]. By reducing the amount of fossil fuels and replacing them with less carbon intensive fuels, like waste and biomass has been discussed as a possible ways to decarbonize the process. Since the kilns are already made to work with different fuels, no large refurbishments would have to be made to introduce larger amounts of waste or bio fuels. It does on the other hand need nationally implemented policies that sort waste and collect it so that it can be used in the cement manufacturing. A lot of waste from construction is not used efficiently in the Nordic countries, meaning that it is deposited or the energy that is actually taken from it is done inefficiently [19, 20]. There are also other issues regarding the efficiency level of alternative fuels compared to fossil, such as them not having the same calorific value, moisture content or/and high concentrations of trace substances. This requires that much of the waste used needs to be pre-treated to ensure high quality cement.

Another initiative in the CemZero project is using plasma technology for heating the furnaces, which makes it possible to electrify the process [20]. Plasma is in physics a fundamental state of matter that is created when a material is heated to a state when electrons are separated from their atomic nucleus and creates a mixture of ions and electrons [20]. In plasma generators plasma is created by letting electrons accelerate between an anode and cathode electrode, which creates an electric arc, meaning that the electrical discharge ionises the air making it conductive. The air, or carrier gas, is then heated to very high temperatures. ScanArc Plasma Technologies AB (ScanArc) is a Swedish company that provides plasma generators that through this technology heats the plasma gas to 3000-500°C [20].

Tests between Cementa and ScanArc have been successfully performed in smaller scales and waiting to be tested in larger scale for industrial purposes [22]. The commercially available generators today can only generate 7 MW, but there have been other test that show possibilities of utilising several parallel generators to fulfil the energy demand. If the thermal process is to entirely be replaced by plasma generators, it puts a great pressure on the availability and sustainability of green electricity [20]. Figure 4.7 illustrates a simplified version how this process could look like.

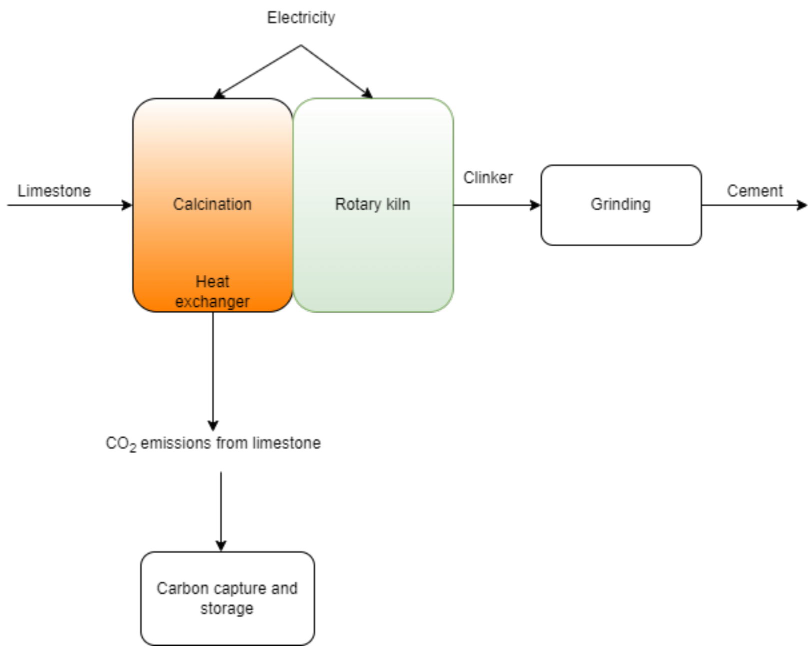

Figure 4.7: Simplifed cement process 2050

4.2.3 Carbon capture and other methods for negative emissions

As mentioned in the previous section, the largest part of emissions does not come from the combustion of fossil fuels in the rotary kilns, but rather in the pre-calcining process where CO_2 is released in the chemical process of turning calcium carbonate (lime stone) to calcium oxide and carbon dioxide separately. Since this part of the process cannot be decarbonized with changes in the energy source or conversion, CCS has to be implemented if a change in alternative binders is to be excluded [23]. There are several different methods to implement CCS, but in general it means that the CO_2-emissions are separated from the flu gases, compressed and transported to a storage site where it is pumped down into the bedrock for permanent storage.

Even if the technology for CCS has been available for quite some time, these processes are very expensive and will need either support from national policies or that actors come together to invest in a joint infrastructure [2, 23]. For individual actors to invest, still implies a great risk because the infrastructure of capturing the CO_2, transporting and storing it is not complete, the technology will not fulfil its purpose, making it a bad investment. Another aspect that makes the cost for CCS uncertain is that there are several different types of technologies, making the cost prediction depend on what type of CCS one focuses on [2]. There are already projects in place for joint infrastructures, like the *Northern Lights* [24] project in Norway who are developing a common infrastructure for CCS and

Första, andra, tredje [25] by the Swedish Energy Agency to develop a support system for bio-CCS [25].

Another aspect is that the transportation of the CO_2 has to be done by ocean transport, meaning that the plants who implement CCS should be close to harbours [25, 2]. The Scandinavian countries are close to the water and there are several possibilities for carbon storage around the Baltic sea. In addition, most of the carbon intensive industries are in close range to the water as well as the possible storage sites [2].

A problem with CCS in cement production today is that the emissions from the process are not only CO_2, and they need to be separated for the CCS to be able to only capture the CO_2 [2]. If the thermal process would be entirely electrified, then the only emissions would be pure CO_2 from the chemical process in the pre-calcining process, which would simplify the CCS. If the CO_2 has to be separated, it also leads to an increase in energy consumption and only reduces the total emissions by 80-90%. On the other hand by combusting bio-fuels in the rotary kilns and implementing CCS, it can lead to negative emissions [2].

4.2.4 Oil Refineries and Oil & Gas extraction

In this section, it is discussed how the oil refineries can decarbonize by either producing hydrogen or bio fuels. The future of oil & gas extraction is also discussed.

4.2.4.1 Oil Refineries in 2020

Figure 4.8 shows how the process of refining petroleum products works today. Crude oil are being heated and different components of the crude oil are extracted. Most of the emissions are being realised in the heating of the crude oil, where both natural gas and refinery gas is combusted [26].

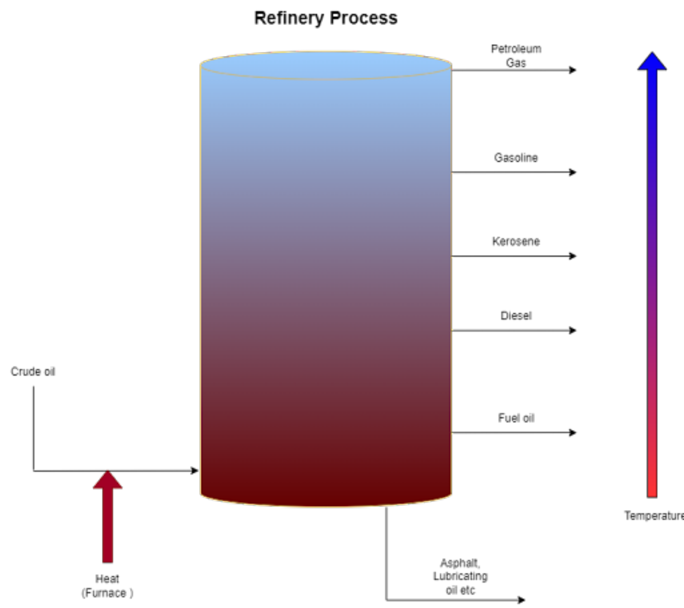

Figure 4.8: Illustration of refinery process 2020

4.2.4.2 Bio Refineries

Uncertainties regarding completely phasing out the fuels and replacing the final product with hydrogen are how big the demands for both jet fuels and hydrogen are going to be in 2050. Therefore another scenario would be replacing the input crude oil in the refineries with biomass. This results in that the products from the refineries would be bio fuels, such as bio-kerosene, biogas, biodiesel, bioethanol and bio-naphta. This puts both pressure on there being a big supply of biomass and also on the transportation sector to transition into using more bio fuels. The increased amount of biomass in the refineries also result in a larger amount of excess heat, that can be provided to the district heat grid.

The process of turning biomass into bio fuels is most often through fermentation or gasification. In gasification, the biomass is separated into carbon monoxide and hydrogen to produce synthesis gas, which in return is what can be used to produce the bio fuels. In gasification the biomass often needs pre-treatment [27]. Fermentation is the basic and natural process of letting the enzymes of microorganisms take one (sugar) molecule and turning it into the desired structure to create the bio fuels. Both of these processes can be used in bio refineries simultaneously as they are fit for different types of raw material [27].

Another aspect of using larger amounts of biomass is that it is a difficult and expensive raw material to transport, and therefore needs densification before it can be transported from where it was grown. This results in a higher energy demand, as for example the densification method pyrolysis requires the raw material to be heated to 500°C so it can be turned into oil or char [27]. Figure 4.9 illustrates the bio refinery process.

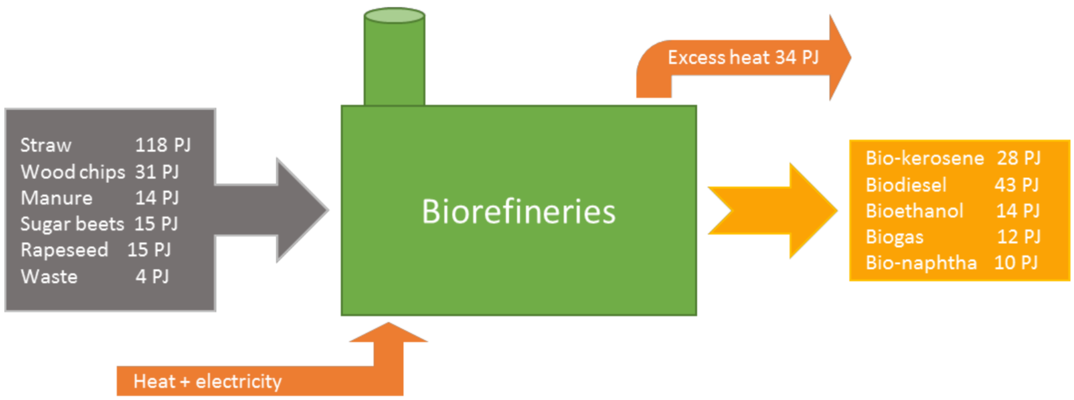

Figure 4.9: Illustration of bio refinery process [28]

4.2.4.3 Oil & Gas extraction

The future of the oil & gas extraction is very unsure. This thesis aims to achieve a carbon free 2050, meaning that there is no place for any fossil fuels in the RES diagrams established for 2050. There are plans to build wind farms around the oil rigs at Norway's coast that are supposed to power offshore oil and gas rigs with green renewable electricity [29]. This would make the more rigs sustainable, but in order to reach the goals of becoming carbon neutral in 2050 the demand for oil and gas products should drastically be reduced. The only country where the oil & gas extraction is included in the RES - diagram is Norway, see Figure 4.1. This was mainly due to the importance of the industry for the country. Hence the big drop in demand the thesis will not proceed with the industry in the RES diagram 2050, probably it will not be economically viable to maintain operation of the rigs and they will therefore be shut down before 2050.

4.2.5 Hydrogen

One scenario that is shed to light in a report by the the Nordic Energy Research is that the demand of oil products that come from oil refineries will be significantly decreased to 2050, while on the other hand renewable products such as green hydrogen most likely will increase [2]. According to the report, the demand for hydrogen could be as high as 135 TWh, which would require more than 20% of the electricity generation in the Nordic countries today. An option for the oil refineries to reduce their GHG emissions, if they do not want to close down, is to revamp their plants to producers of hydrogen

[2].

The production of hydrogen can be done in a number of ways. The majority of the hydrogen that is produced today is by using natural gas. The main process is the endothermic metal-catalysed reforming, which requires high temperatures (1000 - 1200°C) and pressure (20-30 atm), which requires high amounts of energy. Since this process is powered by natural gas, it contributes to quite a lot of GHG emissions and is therefore not preferable in a decarbonation scenario. There are other types of processes to produce hydrogen, that are far less carbon intensive, such as green and blue hydrogen.

4.2.5.1 Green and Blue Hydrogen

Green hydrogen (or renewable hydrogen) is produced using only renewable energy sources and has zero emissions. Energy used in this process is often solar power, wind power or hydro power. Because of the challenges of reaching zero emission, there is a so called *Hydrogen Cleanness Index* (HCI) that shows how "green" the hydrogen products is, meaning how carbon intensive a process is. A process can for example be 80 % green due to some emissions from the production process. Using green hydrogen adds a flexibility and energy storage and transportation to renewable energy sources which without hydrogen would not be possible [30].

Blue hydrogen is produced in the conventional way, using natural gas but utilizing CCS technology to capture the CO_2 emissions. Utilising CCS in this process can reduce the emissions with about 85%. It is important to note that the CCS effectiveness and energy use for the carbon removing process has to be taken into account in the total emissions. It is also important to note that implementing a CCS system would increase the overall electricity required with about 60% compared to a hydrogen plant without CCS. The CCS technology does on the other hand lead to an increased efficiency due to a decreased need of natural gas to about 8-10% because the CO_2 can be put back in the process of producing hydrogen [30].

Even though the cost of CCS technology is quite high, comparisons between blue and green hydrogen shows that blue hydrogen is cheaper to produce. According to the Nordic Energy Research, blue hydrogen is also more energy effective. Blue hydrogen could be preferable because already established plants can be used for producing blue hydrogen [30]. Preem is a company that is operative in the refinery sector and have plans to establish a blue hydrogen plant. It will be built with an electrolyzer with the capacity of 18 MW and is planned to produce 3800 m^3 hydrogen per hour. Such a plant would reduce the emissions by 25 000 tonnes per year [31]. Furthermore, it is argued that green hydrogen with electrolyzers will be the main way of producing hydrogen in 2050 and also the process that is highlighted in the RES diagrams for 2050. This is since fossil fuels will be phased out by 2050 and it is needed to produce blue hydrogen therefore there is no place for it in the RES diagram for 2050.

4.3 Chosen processes

In conclusion, for the steel industry, the most efficient and realistic alternative process is the one suggested by the HYBRIT project, where hydrogen is used as a reducing agent instead of coke. The HYBRIT project is the only new way to produce steel with net zero emissions without having to implement CCS. CCS on the current process is a technology that could also contribute to net zero emissions, but as the steel manufacturing in the HYBRIT project is powered by renewable energy it is considered a more sustainable option.

As for the manufacturing of cement, both the thermal and the chemical processes need to be taken into account. For the pre-calcining process, CCS will need to be implemented. The thermal process with bio fuels is a possible scenario, but will take immense amounts of biomass and still not be able to completely replace the fossil fuels because it is not as dense as the fossil fuels used today. It can therefore not take the furnaces to the temperatures needed, which means that additional CCS technology will be needed to reach net zero emissions. If the plasma technology is implemented, the thermal process would be completely electrified and not need any CCS. It also means that the separation process needed for the CCS can be completely counted out, since there is only pure carbon dioxode being emitted in the pre-calcining process. The processes used in the 2050 scenarios will therefore be plasma technology together with CCS.

For the oil refineries it should be discussed if the oil refineries should completely transform into hydrogen producers. This would have to imply that other sectors, such as the transport sector, are completely independent from the products which they produce, such as diesel and kerosene, to 2050. The average life-span of a car in Sweden is 17 years, meaning that if a petrol-powered or diesel-powered car is bought today, then it is going to need those fuels until 2039 [2]. As for the aviation sector, the demand for kerosene is predicted to not decrease in the future, meaning that there would have to be a low-carbon substitute for this, such as bio-kerosene [32]. The bio fuels that are produced in a bio refinery can replace most of the fossil based fuels used today and is already implemented to an extent in the transport sector [33]. It will be assumed in the 2050 RES-diagrams that all transport fuels are replaced with bio-fuels.

However the commercial use for hydrogen technology is still expected to increase to 2050, which is why the processes used for the 2050 RES-diagrams in refineries are both bio refining combined with production of hydrogen. It is still a question if blue or green hydrogen should be produced in these refineries. Even though the technology of today suggests that blue hydrogen is more efficient, the goal is to reach net zero emission, which will not be achieved if the refineries produce blue hydrogen. In addition, blue hydrogen still needs natural gas for the process, which is a fossil fuel, and green hydrogen is considered a more sustainable option. Therefore green hydrogen will be the process that is utilised in the RES diagrams for 2050.

4.4 Industrial Energy Systems

This section attempts to answer research question 2 by presenting the RES-diagrams for the 2050 scenario in each country that illustrates the changes in the energy supply mix caused by the changes in the industrial processes described in the section 4.2

4.4.1 Sweden 2050

The Swedish agency Energimyndigheten put forth a report from March 2021 called "Scenarios on Swedish energy-systems" [34] every other year. This report highlights five different scenarios for the year 2050 in Sweden. The report from Energimyndigheten will work as a reference for creating an RES-diagram for year 2050 in Sweden together with extra material on the focused industries.

The different scenarios listed in the report is (1) *Reference EU*, (2) *Lower BNP*, (3) *Lower energy prices*, (4) *Further actions* and (5) *Electrification - Accounts for the changes in further actions but with a higher utilization of electrification.*

This thesis used the scenario *Electrification* as a reference model. The scenario doesn't account for all of the electricity needed for the electrification of iron an steel industry, only for 25 TWh of the 55 TWh needed. This was accounted for in the RES-diagram by increasing the total electricity production of wind-power since SSAB and LKAB will use wind-power energy primarily to create hydrogen used for steel production [34].

The electrification scenario was used due to several different factors listed below,

- The electrification scenario is best in line with Sweden's political goals of reaching net-zero fossil fuels within the transport sector [35].
- This scenario fully utilizes developing technologies like HYBRIT and CCS which has a high

potential for reducing Sweden's fossil fuel use.

- Sweden has a high potential for electrification and a expansion of both wind, solar and nuclear power [35].

The potential for electrification in Sweden is immense but will need a vast amount of low-emission energy to replace fossil fuels that are very efficient. In this scenario the electricity prices is higher compared to the other scenarios which makes it profitable to build new nuclear plants and increase the expansion of solar and wind power. The RES-diagram also accounted for currently non-implemented technologies, primarily Hybrit, plasma generators and electrification of mines. For more information see section 4.2. The 2050 RES-diagram for Sweden can be found in Figure 4.10.

As seen in the RES-diagram for year 2050 the energy supply is 582 TWh compared to 508 TWh 2020, this is due to the rapid expansion of low-emission electricity producers and the out-phasing of fossil fuels, see 4.10

The biggest energy source is estimated to be wind power generating 126-156 TWh compared to 27.5 TWh for 2020 which is an increase of 458-570%. This will be possible with more off-shore wind-power plants as well as the expansion off land based wind power. It is also necessary to build more efficient and more extensive in size to reach the energy production [2] [34].

An uncertainty factor in this model is the amount of electricity produced from nuclear power. This scenario assumes either an increase in electricity price which makes nuclear profitable or a technical leap in the technology which makes it more efficient. In the RES-diagram Sweden has a increased electricity production from nuclear by 47.3 TWh 2020 to 60 TWh 2050 which is a 28% increase [34].

Solar power is another energy supply that is likely to increase in 2050. In the different scenarios presented by Energimyndigheten, consumption is likely to increase from 1 TWh in 2020 to 8.6-11 TWh in 2050 which is an increase by 860-1100%. In the RES-diagram (Figure 4.10) the more extreme case is accounted for [34].

The expansion of hydro power in Sweden is limited due to political unwillingness, as it has a negative impact on the ecosystem near the plants. Therefore, hydro power generates almost the same amount of electricity in 2050 as in 2020 [36].

As can be seen in the RES-diagram for 2050, see Figure 4.10, the industry's energy use has increased from 136.3 TWh to 195.8, which represents more than 50% of the total end-use of energy. This is mainly due to the electrification of the iron and steel industry, which makes the industry increase the demand for energy by more than 300% and exclusively electricity. Compared to 2020, the iron and steel industry has the potential to transition from fossil fuels as a reducing agent to hydrogen, see 4.2 for more information. This will cause a drastic increase of energy within the sector. In this case it is estimated that the iron and steel industry will require 50-55 TWh energy [18]. Since steel is an alloy of iron and coal, there is some use of coal in the end process. It is estimated to be around 0.6 TWh. This process is negligible in terms of CO_2 emissions because coal is contained within the steel [14].

There is also an increase in electricity in the sector of non-metallic minerals by using heat transfer with plasma generators in rotary kilns that would replace the use of fossil fuels. Together with the technology of Carbon capture and storage (CCS), which will capture the emitted CO_2 emissions, see 4.2 for more information. This will lead to an increase in electricity by 4-5 TWh, which will replace all fossil fuels. Comparing this to the 2020 scenario, this would make the cement industry completely CO_2 neutral.

The refineries change a lot in the 2050 scenario, both in their input material and the end products that they produce. Refineries use biomass and electricity to produce bio fuels and hydrogen. This means an immense increase on the supply side, where the demand for biomass increases from 140.7 TWh in 2020 to 192.6 TWh n 2050. The RES-diagram for Sweden is shown in Figure 4.10.

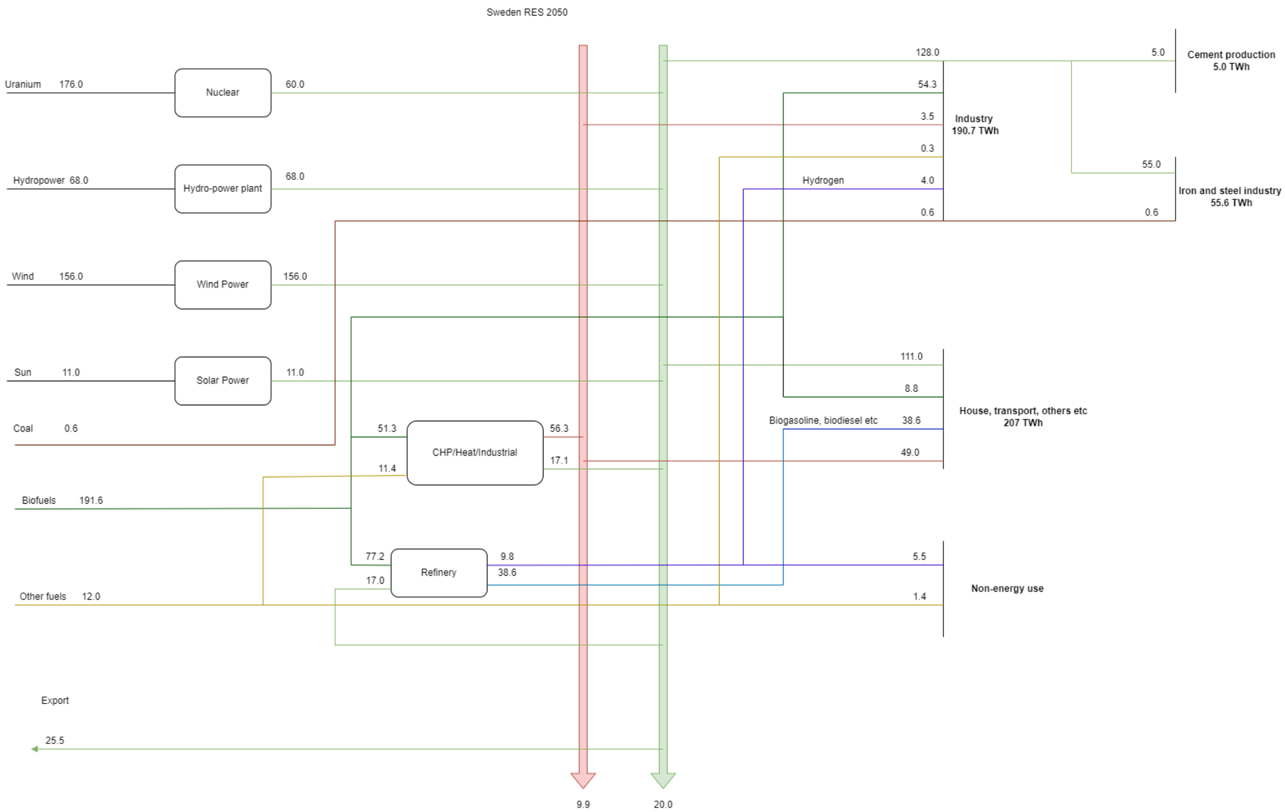

Figure 4.10: RES Diagram over Sweden 2050

4.4.2 Norway 2050

Unlike Sweden, Norway has not published an official energy prediction for 2050. Other reports has therefore been used to get a understanding of how Norway's energy consumption and production may look in the future. The federation of Norwegian Industries together with Det Norske Veritas (DNV) have produced a report on a scenario of how the energy consumption and production may look in Norway 2050 [37]. The paper presents that the expected electricity demand for 2050 is about 250 TWh. When it comes to the electricity production it is presented that wind power will most likely play a bigger part with both offshore and onshore wind power production. Together they will produce about 90 TWh of electricity which is about ten times bigger than what was produced in 2020. It is also presented that fossil fuels will probably be replaced with renewable electricity production such as wind and hydro power. When it comes to bio fuels it is presented in the report that about 18 TWh of bio fuels will be used. This contradicts to what a report published by Nordic Energy Research states, where it is presented that it may be up to about 60 TWh of bio fuels and waste. The amount of bio fuels in the RES-diagram is therefore in the middle of these reports [38]. To produce the amount of bio fuels needed to the industries that use them, the efficiency of the biorefineries demands 71.3 TWh [28], see Figure 4.11, which is a big increase from 17 TWh in 2020, see Figure 4.1.1.

It was also presented in the report done by DNV that the industry sector consumes almost 90 TWh of electricity and 21 TWh of hydrogen. The increase of electricity demand will partly be due to new industries such as battery factories that will demand large amounts of green electricity. Other industries that will demand a vast increase of green electricity is alumina and electrolysis-based hydrogen production and green steel [37].

The energy mix will most likely change, the reason for that is that the hydro power is already well developed and will therefore not increase as much as needed. In the RES-diagram, wind power will close this gap, see Figure 4.11. The electrolyzers also provide the grid with 33.6 TWh, which helps with the electrification of the industry sector. Furthermore it is presented that Norway will have a relatively large hydrogen production of around 22,5 TWh. In the RES-diagram for 2050 there is not a households or transport part, these parts were put together as "other". The reason for that was that it was the industry part that was interesting for this report and specifically the refineries for Norway. Most of the data of the supply of electricity for the 2050 RES-diagram was based on the data given by DNV [37]. The RES-diagram for Norway in the 2050 scenario is shown in Figure 4.11

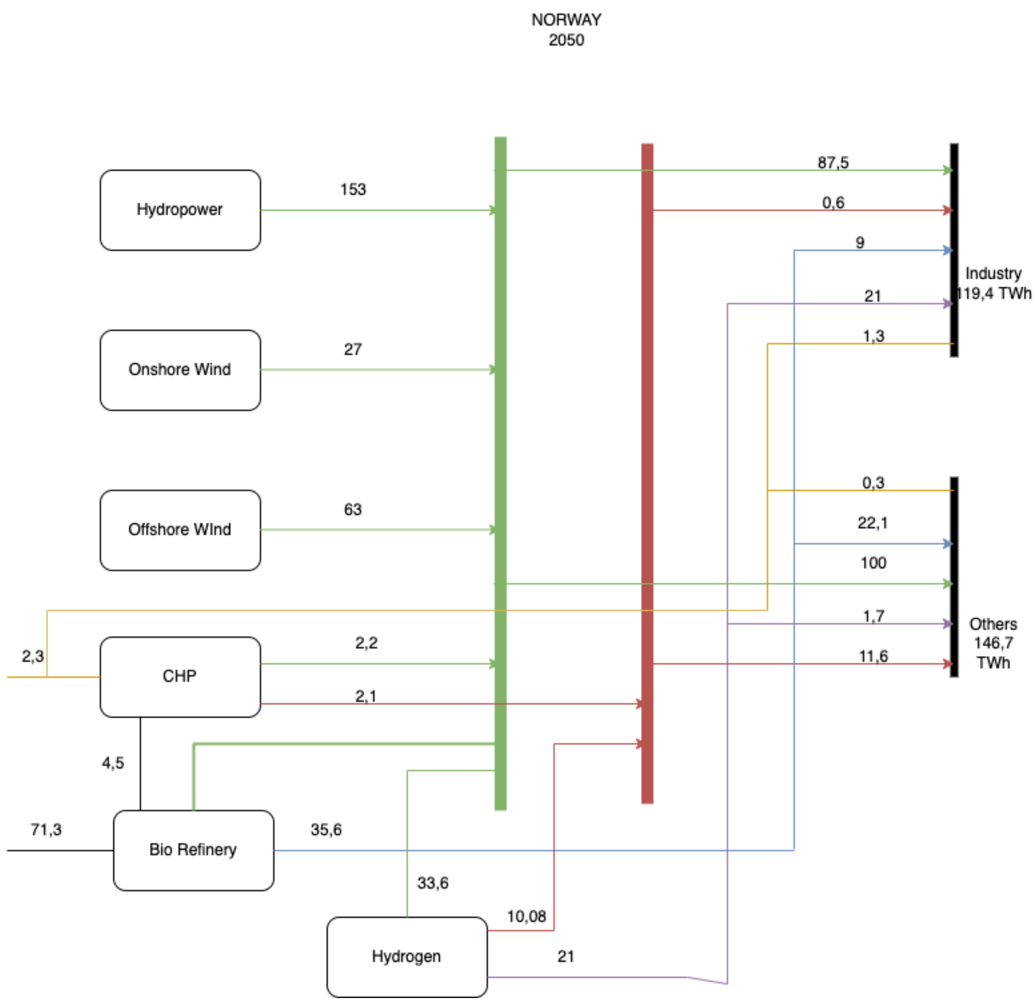

Figure 4.11: RES Diagram over Norway 2050

4.4.3 Denmark 2050

In a report provided by S. Ropenus and H.K Jacobsen, "A Snapshot of the Danish Energy Transition", it is discussed that the Danish energy strategy launched already in February 2011, where a number of concrete goals where established [39]. The aim of the goals was to gradually phase out fossil fuels and replace them with renewable energy sources. In 2030 all coal and oil burners should be phased out from the power stations and by 2035 they are aiming on 100 % renewable production in electricity and heat supply. This will be achieved through energy optimisation in the transport and households sector [28]. Regarding the industry sector and more specifically the cement industry which is the studied industry for this country, Denmark will most likely have to use plasma technology to maintain their production rate of 3 million tons in 2050 [40]. This will require vast amounts of electricity, which is further discussed under section 5.

In the future, the foundation of Denmark's energy supply lies within energy sources such as wind power and biomass [39]. Denmark does not have any plans on building a nuclear power plant. Furthermore, they are not planning to build any hydro power plant neither, this is mainly due to their unfavourable geographical conditions. Denmark does not have any high mountains nor elevations which are required to build viable hydro power plants. It is highlighted that extended interconnections in the grid with neighbouring countries such as, Sweden, Norway and Germany will play a crucial role for the energy transitions [39]. Since Denmark relies on a majority of intermittent energy sources it needs to have the option of selling surplus energy to neighbouring countries and importing electricity when needed.

In the report provided by Ropenius and Jacobsen a few different scenarios for Denmark's future energy system is listed. The scenarios are all in line with the vision of becoming fossil-free by 2050 and covers all energy users in all sectors. All of the scenarios also contains wind power and biomass as the major energy carrier and electricity producer. The scenarios are described as:
Wind: This scenario entails wind and solar power as the major energy producers and bio energy is limited to around 70 TWh which makes it possible to supply it domestically.
Hydrogen: This scenario also accounts for a vast hydrogen production, where you benefit from the intermittent electricity production. When there is surplus electricity in the grid, it is used to produce and store hydrogen, which can be used when the electricity production is lower.

The energy end use will rise significantly in the industry sector. This is mainly due to the fact that many industry processes, such as the cement industry, are to be electrified and will be more energy intensive. As can be seen in Figure 4.12, the electricity supply to the cement manufacturing increases to 5 TWh, from 1.8 in 2020, see Figure 4.3. This significant increase is due to the implementation of the plasma technology for the cement manufacturing. For Denmark, the amount of biomass is immensely increased from 23 to 103 TWh, of which 55 TWh goes to the bio refinery, see Figure 4.12. The production rate in the industry sector will also have to increase in order to meet a higher expected demand in the future. Regarding the household sector the energy consumption is expected to decrease because of more efficient heating and electric household items [28]. Many of the households is also predicted to produce their own energy via, for instance solar cells. This is then not shown in the RES diagram since they are not taking any energy from the grid or the district heating network.

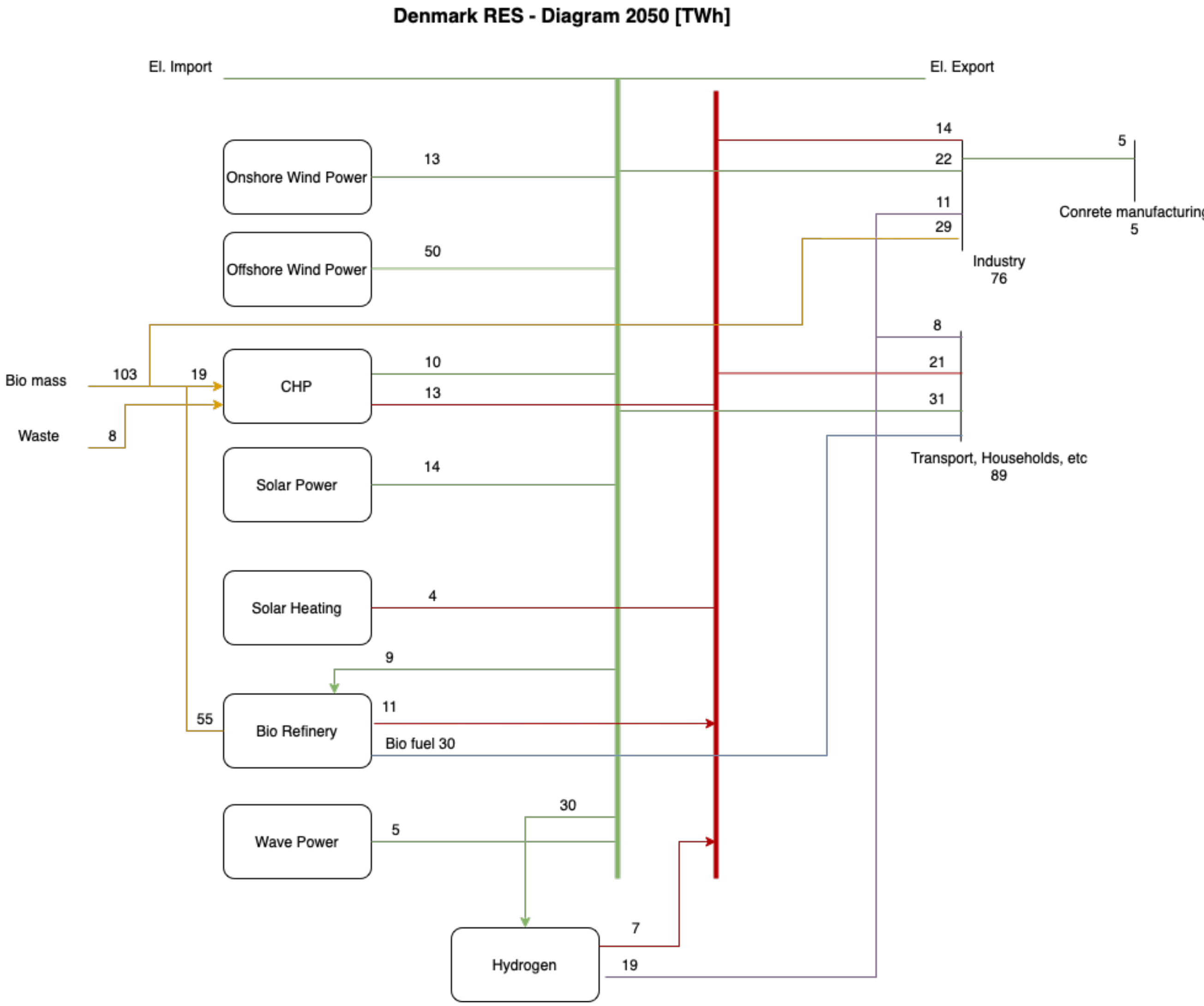

Figure 4.12: RES Diagram over Denmark 2050

5

Discussion

This section is an analysis and discussion of the results. The biggest challenges with the future energy system is discussed. The benefits and drawbacks of the chosen methodology is also discussed

5.1 Energy Supply & Demand

The biggest difference when comparing the 2020 RES-diagrams with the 2050 was the increase in electricity due to it being what replaces the fossil fuels in many of the industries, except for oil refineries. In Sweden it increases with 100%, in Norway 80% and in Denmark 130%. This puts a great pressure on the electricity coming from green energy sources for the industries to really be carbon neutral, which is why the amount of energy from wind power is increased to a great extent in the 2050 RES-diagram for all the countries. There is also some increase in solar power even though it is more limited in size. The other forms of renewable energy sources like hydro power could not be expanded more due to geographical and political limitations, like the preservation of eco-systems.

One major difference with Sweden's energy supply compared to the other Scandinavian countries is the use of nuclear power. As previously stated in section 4.4, nuclear releases close to no CO_2 emissions to the atmosphere. Therefore, it is plausible that nuclear could play a long-term role as an energy supplier until new breakthroughs are made in other technologies. Another aspect is that Sweden is reliant on Nuclear power in 2020, there could potentially arise issues if it were to be out-phased. One of these issues is supplying the electricity for electrification of industries. Another issue could be that Sweden would have a problem in its electricity grid with too much intermittent electricity.

Biomass is likely to be a coveted resource reaching the COP 21 goals for 2050. In addition, a surge in biomass demand is expected for all Scandinavian countries, which can be seen in the 2050 RES-diagrams; see Section 4.4.

There is a big uncertainty regarding the role of petroleum products in 2050. In many of the scenarios listed in section 4.4 petroleum products are still used in different quantities, but in this thesis all of the petroleum products from refineries in 2050 are replaced with renewable sources, such as bio fuels, hydrogen and electricity from the grid, see RES-diagrams in section 4.4. As seen in the RES-diagrams for 2020 (section 4.1), many of the products that come from the refineries go in to the transportation sector, such as gasoline and diesel-oil. In the 2050 scenario, it has been assumed that the transportation sector can be completely powered by green energy sources, such as green electricity and biofuels.

Therefore, there is an uncertainty in the result, because it is impossible to know if the fuels used in for example the transportation sector will be completely phased out in 30 years and in addition there is no suggestion in this thesis how the sector could transition. Since the thesis focuses on decarbonization, the carbon neutral scenario was selected, which could be realistic in terms of technology, but might be more difficult to implement due to economical aspects.

5.2 Credibility of Results

When discussing whether the results are plausible or not, some factors may be taken into consideration. Since the renewable electricity production is mainly driven by expansion of wind power it is important to note some uncertainty factors regarding its implementation. The electricity in 2050 for the studied countries will therefore revolve around a higher percentage of intermittent sources than in 2020. This will mean that the share of intermittent electricity production will increase, which means high production when weather conditions are favourable and none when the weather is calm. Therefore, it is possible that the electricity grid needs reformation and development in order to cope with this. Variation management techniques to manage the increased variations introduced in the grid, such as adapted hydrogen production will have to play an important role. For example, the ability to store intermittent electricity in hydrogen when it is overproduced and use it when conditions are worse. In Sweden and Norway, there is a security of supply in that nuclear power is not dependent on weather conditions and hydro power is flexible in terms of electricity output. But in Denmark there is only wind power and solar power that are both intermittent. They will therefore probably have to extend their interconnections to other countries to be able to import electricity when weather conditions are not favourable. An issue with this is that even if the domestically produced electricity is renewable and green, there is no guarantee that the imported electricity will be produced from renewable sources or free of emissions.

When it comes to the wind power production there may be problems in regards to building all the wind turbines in time. All the countries will have a high demand in the production of wind turbines and producing enough both onshore and offshore wind power can therefore be problematic in terms of the time aspect and supply chains. Production capacity in terms of wind turbines must increase rapidly to meet the required electricity demand in 2050. Another relevant aspect of this problem is that the demand for both cement and steel will increase since these are the materials that are most used when building on- and offshore wind turbines. This in turn will put even more pressure on the cement and steel industry to be more sustainable since the demand for their products also will increase to 2050.

As previously stated the demand of biomass will increase. This could be problematic in regards to both a cost and sustainability concern, since it is a limited resource that requires a great amount of space in a geographically limited area. Therefore, it would likely lead to an increase in prices. For countries like Norway and Denmark, the supply of biomass can therefore be an issue in the future. They will probably not be able to supply their own demand of biomass and will therefore depend on importing it. Being heavily dependent on other countries to supply the energy of the country leads to a risk in terms of supply security. For example exporting countries can increase the prices for the biomass quite freely if other countries are completely dependent on them, or stop exporting when they need it themselves. Sweden on the other hand has roughly 70% of the land area covered by forest[41] and would likely be able to self-sustain the biomass supply. Due to the increase in demand for biomass and biofuels, the prices of biofuel will likely increase. Another relevant aspect with regards to biofuels is the potential competition between different sectors for biofuels. Due to the uncertainties regarding the supply and surge in prices of biomass, industries with the possibility using electrification too remove fossil fuels would likely benefit from this.

New technologies may occur in the next 30 years which cannot only be accounted for both producing energy but also for reducing emissions. These were not accounted for in this report and might have had a big impact on the end result. There are also technologies which are being developed but at an early stage which could impact the rate of electrification, since these technologies have a low rate of ever seeing the broad daylight these have been excluded as well. But technologies that are in late developed stage but not on the market for 2022 like the electrification of the steel industry, CCS or using plasma technology instead of fossil fuels in the cement industry are accounted for in the report. It is estimated that these technologies have a good succession rate of implementation and are accounted for in the 2050 scenario since these technologies could have a large impact on the industry transition from fossil fuels to electrification. There is undoubtedly a risk for the above-mentioned technologies to not be competitive enough or hard to implement on a large production scale.

There are also some uncertainties regarding if CCS will be able to be implemented in full scale by 2050. For the CCS technology to be in place by 2050, investments in common infrastructures from actors and support from national policies are imperative. The uncertainty of the cost of CCS is to a large extent what holds back these investments. This is both because there are several different types of technologies and because not many CCS-plants have operated on a larger scale before. At the same time, climate change mitigation becomes more discussed and actions are taken, like the tax on CO_2 in the EU, motivating actors to lessen their emissions. The CCS technology needs to be cheaper than the taxes on CO_2-emissions for it to be worth the investment. When it comes to CCS in the cement manufacturing, it is also worth discussing if the plasma technology is the best option regarding the use of CCS, since using biofuels instead can lead to negative emissions. There is a possibility that there will be a market for negative emissions rights in the future, which could imply that actors can sell their negative emissions rights, making the CCS technology more viable.

One of the biggest issues with the implementation of these technologies is for them to be economically competitive. This is because these industries tend to require a large amount of investments and new processes to erase fossil fuels. For example, the electrification of the iron and steel industry (see section 4.2) requires a great amount of energy, about 55 TWh [18]. These numbers can vary though, one of the reasons is that its hard to estimate. Another reason for the variation can be that different calculated numbers accounts for different processes. Both the energy and cost is something that is the biggest question mark regarding the electrification of the steel industry. To be able to compete with the regular blast furnace that is used in iron and steel production today, the efficiency in regards to both cost and energy has to be increased. For the electrification of iron and steel industry to be economically justifiable the CO_2 market has to increase. Due to higher costs for CO_2-equivalents hydrogen may be cheaper. These new technologies are also very energy consuming compared to using fossil fuels for the same process. The production of steel was for example using 16.5 TWh of 2020 and is as previously stated estimated to use about 55 TWh in 2050 4.10.

As stated previously, electrification and decarbonization of the investigated industries will require investments in terms of electricity, new processes, and new technologies adopted such as CCS. For example, the production of steel would require more energy. This is likely to increase the price of the output of these industries, for example, steel, cement, biodiesel, etc. Therefore it could be an issue regarding the competitiveness for these competing products made from old processes with the use of fossil fuels. One solution to this problem is the European Union (EU) initiative Carbon Border Adjustment Mechanism (CBAM), which is a trade act, which means that EU countries that import goods such as steel and cement will buy carbon certificates. Those certificates would correspond to the carbon price that would have been paid had the goods been produced under the EU's carbon pricing rules [42]. This would mean that imported products that are carbon-intensive will struggle to compete with more renewable alternatives. There are already regulations in the EU which address these issues such as the Emission Trading System (ETS). This regulation sets the cap of GHG that can be released from industrial processes in some sectors. The permits to release GHG from industrial processes are bought on the EU emission market. While the ETS regulation helps with emission rights within the EU, the CBAM regulation will increase the exports of green steel and cement [42] [43]. The CBAM would likely benefit Sweden and Denmark's export as both countries are in the EU. However Norway would probably not benefit from this regulation as they are not in the EU and haven't adopted to such regulations. But there are other countries and regions that have adopted similar regulations. Some of them are California, Japan, and Canada [42].

5.3 Methodology Discussion

The chosen methodology offered a wide variety of possibilities in terms of mapping energy systems throughout a country. It provided a good overview of how both energy was supplied and consumed within the specific country. It was also very efficient when working with big complex system with many different energy carriers. The methodology succeed to structure the large energy systems (countries in this case) that sometimes could be messy and hard to structure. Although the main methodology was well suited to the research questions, it also came with some restrictions on the results obtained. One of the restrictions is that, as already discussed, the RES only shows an overview picture of an entire energy system and it is not possible to zoom in on a particular processes in the diagram. This is why it was suitable to complement the RES with a more specific explanation of the various industry processes.

Another restriction was that the RES only treats energy flows and not material flows. The material flows also plays a crucial role in the different industry transformations. For instance it would be interesting to investigate the specific material flows in the concrete industry. It is a rather complex process which the RES diagrams fail to show.

In addition, RES diagrams show a static picture of the system, lacking therefore the temporal aspects that we discussed earlier. Variations in wind speeds for example and the need to variation management techniques, while essential for planning the energy system, cannot be reflected in a RES diagram.

When it comes to the gathering of data, it became clear that the different countries are unequally solicitous to provide information regarding their energy use. For example, Norway has not published an official energy prediction of how the energy consumption will look in 2050. This differ from for example Sweden which have presented a report of potential scenarios for 2050. One reason for this may be that Norway produce a lot of fossil fuels product today and sells to other countries and therefore do not want to do a report that shows that this probably will not be something that will be as big in the future. In other words the reason for Norway not presenting an official report on potential outcomes for Norway's energy use in the future may have a financial reasoning behind it.

5.4 Further Studies

When it comes to further studies other sectors could be taken into more considerations such as transport that is both carbon intensive and energy intensive. By taking more sectors into consideration a more holistic perspective can be presented to the reader. Another thing that could be taken into more consideration is the political aspects of energy consumption and supply in the different countries, how the similarities and differences may affect the future for the countries. There could be new laws and regulations that may affect the future energy landscapes, for example if no cars driven by fossil fuels are allowed by a specific year. It could also be interesting to investigate more of the economic aspects and how they may affect the future.

Since the report emphasize on the study of energy flows it could be complemented with studies that involved material flow as well. This would be beneficial since the studied industries are highly material related especially the iron and steel industry as well as the cement industry.

Methods such as the linear electricity system optimization model (ENODE) could also be interesting to apply in the report to complement the RES-diagrams. When using such a model temporal aspects can be taken into account which is hard to present in a RES-diagram. For example for the intermittent electricity production that can produce different amount of electricity different days and even hours. Replacing for example 1 TWh electricity production from coal plants with wind power can look sufficient in a RES-diagram, when in reality it will not always be able to meet the demand. When having such a fluctuation electricity production can lead to a great fluctuation in the prices when for example importing electricity [44].

6

Conclusion

This thesis has aimed to investigate the relationship between industry structures and low-carbon energy transition in the Scandinavian countries. Two main research questions were formulated: the first entailed the most carbon intensive industries, which were found to be the refining industry, the steel manufacturing industry and the cement manufacturing industry. In both the steel industry and the cement industry, different chemical reactions in the two processes contribute to a large part of their emissions. For the cement industry, the pre-calcining process is the main source of emission and for the steel industry the use of coke as a reducing agent is the the main source. In the refining of petroleum products the combustion stage of refinery and natural gas was the main source emission. The RES-diagrams for each country in 2020 highlighted that the energy flows consisted of much fossil fuels in all of the chosen industries.

For both the steel and the cement industry, there are futuristic technologies in place that could enable operations without emitting any GHG emissions. For the cement industry the thesis argues that a plasma technology in combination with CCS holds high potential for implementation by 2050. This will allow for the industry to reach zero emissions. In the steel manufacturing in 2050, hydrogen will be used as a reducing agent instead of using coke. This innovation will allow the steel industry to also reach zero emissions. Although the two technologies are vital for the the two industries future, there are uncertainties on whether it is possible to provide vast amount of green electricity that is needed for the two technologies to work. This is also something that was shown in the RES diagram for 2050. Regarding the refining industry it was concluded that it will be transformed into solely producing bio fuels in all the couturiers by 2050.

The RES-diagrams for 2050 showed that the overall energy use in the industry sector as a whole will drastically increase. Consequently, phasing out fossil fuels is likely to increase the demand for electricity and biomass. Our results show that wind power will constitute the largest part of the green electricity generation. This raises the question regarding the security of supply to the electricity grid with a larger share of intermittent electricity production. It is then important to assess the possibility to produce the required amount of wind turbines until 2050.

Finally, this thesis has been investigating three of the most carbon intensive industries in Scandinavia that all strives for carbon neutrality in 2050. The thesis has shown that these industries contributes with noticeable amount of emissions and that they need to find other solutions if the Scandinavian countries will have any chance of reaching carbon neutrality by 2050. Furthermore, the thesis has shown that there are greener alternatives to the processes that are used today and that allows for a phase out of fossil fuels. But the transformation of these industries have to take place at the expense of an increased electricity consumption.

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