

The Challenge of Providing Sufficient Grid Capacity for Electrification to Be a Key Factor in Achieving Climate Neutrality Until 2045

- A national and regional demand analysis investigating the future electricity demand and the grid operators' perspectives on large-scale electrification in Sweden

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Abstract

The purpose of the thesis is to contribute to grid planning and public debate about how the electric power system can cope with electrification and decarbonisation. The thesis is based on the assumption that Sweden, in accordance with the climate goals, will achieve climate neutrality by 2045.

Based on a literature review, an analysis is made of how different scenarios predict the future national electricity demand up until 2045 and identifies the underlying drivers for changes in electricity demand. A more detailed analysis based on results from a literature review and interviews with industry representatives is made for four chosen regions, Norrbotten, Västra Götaland, Stockholm and Skåne. For each region, estimates are made of how high the electrification potential is in the industrial, transport, residential and service sectors.

The prerequisites for the electricity grid to handle the identified electrification potential, in terms of grid capacity, have been analysed in order to highlight what challenges there are for large-scale electrification to be a key factor in achieving the climate goals.

The general belief in the studied scenarios is that the national electricity demand will increase until 2045. The investigated scenarios predict increases resulting in an annual national electricity demand of up to 207 TWh in 2045, corresponding to an increase of almost 60 %. The most significant increases are due to decarbonisation in the industry and transport sector.

The regional analysis shows significant electrification potentials in the investigated regions. A few industries stand out with dramatic increases, Borealis AB in Västra Götaland shows an electrification potential of 8 TWh and 1 000 MW and SSAB in Norrbotten shows an electrification potential of 9 TWh and 900 MW. Significant electrification potentials in the transport, residential and service sectors have been identified in metropolitan areas, i.e. in the region of Stockholm, Västra Götaland and Skåne.

The grid analysis shows that it will be challenging to increase grid capacity at sufficient speed. It is concluded that there is currently insufficient grid capacity to meet large-scale electrification, and that the grids need to be reinforced. However, the concession process for grid reinforcements is considered too slow to meet the demands that arise, primarily in the industry sector. Three ways to address this challenge have been identified:

- If the permission process for electricity grid expansion does not change and the industry is to choose the electrification route, this needs to be decided before 2030 in order for reinforcements in the electricity grid to be ensured before 2045.
- Speed up the permit process to allow shorter lead times for power grid expansions.
- The industry choose another route for decarbonisation than electrification.

The overall conclusion is that new approaches for expanding the electricity grid will be required if large-scale electrification is to be a key factor in achieving the climate goals in 2045.

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1. Introduction

As a result of global warming becoming a more worrying topic, there is a growing global debate regarding climate change. The Paris agreement settled in 2016 has set a long-term goal to limit the global average temperature increase to below 2 °C (UNFCCC, 2020b). The Paris agreement has resulted in climate targets at the EU and national level. The target on the EU level is to become climate neutral until 2050 (European Commission, no date b).

According to Sweden's climate targets and climate policy framework from 2017, Sweden will have net zero emissions by the year 2045 (Prop. 2016/17:146, 2017). In order to achieve this goal, a significant societal change will need to take place. Rissman *et al.* (2020) believe that in order to be able to fulfil the Paris agreement, global decarbonisation of all sectors needs to happen in tandem. Grubler (2012) states in his paper about energy transitions that:

The need for the "next" energy transition is widely apparent as current energy systems are simply unsustainable on all accounts of social, economic, and environmental criteria.

Vrontisi *et al.* (2019) writes about decarbonizing the European energy system and mentions electrification as a crucial element for reaching the climate targets. Electrification of energy-intensive sectors with considerable use of fossil fuels is, by both industries and politicians, seen as an essential part in the reduction of greenhouse gases (Swedenergy and Fossil Free Sweden, 2020). The industrial sector and transport sector accounted for almost two-thirds of Sweden's total greenhouse gas emissions in 2018 (Swedish Environmental Protection Agency, 2019d) and will, therefore, play a significant role in the transition. **Figure 1** shows final energy use in Sweden between 2013-2018 (Swedish Energy Agency, 2020a), and, overall, no significant changes have occurred. However, a significant increase of biofuels in the transport sector can be seen.

The electricity demand has been relatively constant at around 130 TWh, excluding transmission losses, during the last 30 years (Swedish Energy Agency, 2020a). However, it is predicted to increase despite the implementation of new energy efficiency measures (Stattnett *et al.*, 2019).

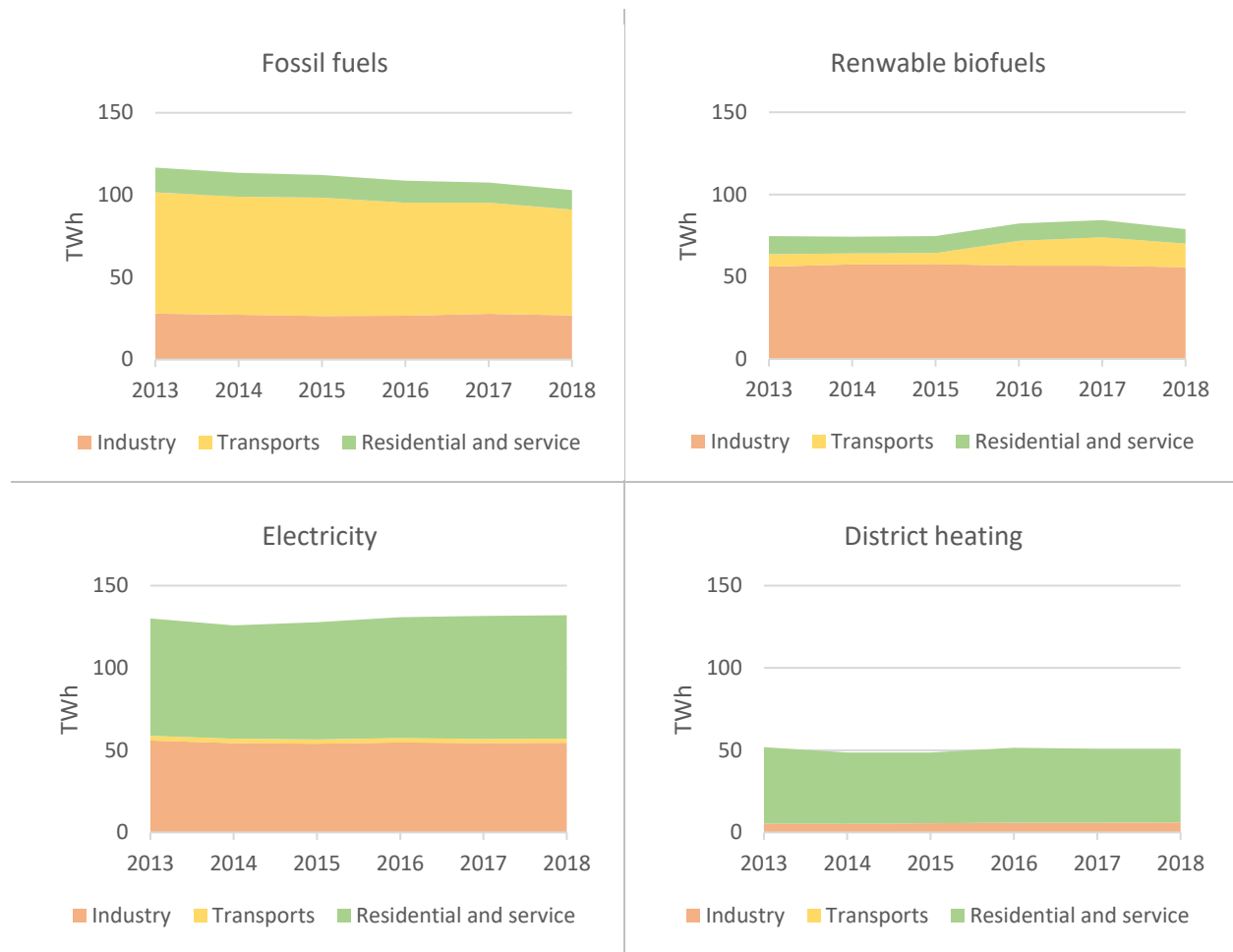


Figure 1: Final energy use in the industry, transport, and residential & service sector between 2013-2018. Based on data from the Swedish Energy Agency (2020a).

The electricity demand in Sweden is expected to increase up until 2045 (Stattnett *et al.*, 2019; IVA, 2020). However, different sources report different scenarios, and the reason why scenarios are different depends, among other things, on how much will be electrified in the existing society, the establishment of a new type of industries and economic growth (NEPP, 2015). Interest in establishing data centres in Sweden has increased and is a good example of what may lead to a new electricity demand (Svenska kraftnät, 2019a). It is not uncommon for this type of data centres to require 300-500 MW of electricity and describes that an electricity requirement of this size can be compared with the electric power demand for a city like Västerås (Svenska kraftnät, 2019a).

Increased demand for electricity will risk capacity shortage in the grid if not the right measures are implemented, and this is an issue that is being raised more and more often in public debate (Capuder, 2019; Medelius-Bredhe, 2019; Norhrstedt, 2019). All the Nordic countries are currently having problems with power adequacy due to an ageing grid, closure of local production, and increased local power demand (Stattnett *et al.*, 2019).

There is currently a lack of capacity in several Swedish metropolitan regions, including Stockholm, Uppsala, Västerås, Mälardalen, Malmö, and Helsingborg (Wiesner *et al.*, 2019). The problem is not considered to be as acute in the Gothenburg region, but capacity shortages in the electricity grid are expected to occur in the future (Wiesner *et al.*, 2019). The consequences of capacity restraints in the electricity grid are that the already existing companies cannot expand their production, the establishment of new companies gets more complicated, and the possibility for cities to develop and expand is limited (Wiesner *et al.*, 2019). If the expansion of the electricity grid does not manage to keep up with the increasing demand Sweden risk to miss out on 150 billion SEK annually in socioeconomic income by 2030 (Pöyrö, 2018), other consequences of capacity shortage can be that the electrification of the transport sector and processes in the industries needs to be postponed and risk not reaching the climate goals (Pöyrö, 2018).

Svenska kraftnät (2019) reports that the system cost of Sweden's electricity system is assumed to increase due to reinvestments, new production, investments in the transmission and distribution systems, as well as in other system services. The challenges that the electricity grid faces and where they will arise will depend on which path the development will take in different regions.

A competitive advantage for Sweden is a stable electricity system with high security of supply and relatively low and stable prices, which has led to the establishment of electricity-intensive industry (Liljeblad, 2016). Continued electrification of the industry as well as in the transport sector and cities will result in a greater need for electricity supply and distribution. In order to continue to be able to have competitive conditions in Sweden, the expected increase in electricity demand needs to be met in a way where stable prices and high security of supply is retained (Swedenergy and Fossil Free Sweden, 2020). As the proportion of intermittent electricity generation increases and the proportion of electricity production possible to plan, in the form of for example nuclear power, is assumed to decrease, there is an uncertainty in how prices in the electricity market will change (Åhman, 2016).

1.1 Problem statement

The Swedish energy system is facing a big transition when phasing out fossil fuels and replacing them with fossil-free energy in order to reach the climate targets in 2045, meaning climate neutrality. In this transition, electricity will have a central role meaning that challenges will arise when even higher pressure is put on the already strained electricity grid. Ruhnau *et al.* (2019) conclude in a study of the German energy system that the higher the targets are set for emissions reduction, the higher increase in the demand of renewable electricity can be expected. Sataøen *et al.* (2015) mean that the two most dominant driving forces for grid development in Sweden are bottlenecks in the transmission grid and climate policies.

A hypothesis is that different scenarios differ significantly in the estimate of future electricity demand. Therefore, the planning of the electricity system is made more difficult when different actors have different views on future demand and when responsibility is not clearly defined between actors. Palm (2008) described this already in 2008 in an article stating that the market deregulation in 1996 has led to small or non-existing incentives for private energy companies to invest in grid infrastructure. Expansion of current and new cables is usually preceded by long planning processes, where a new transmission line can take between 10-12 years to build (Svenska kraftnät, 2019a). Today, there are already capacity shortages in some metropolitan areas. It is crucial to be prepared for possible outcomes of electricity demand until 2045 to avoid that the electricity grid will be a bottleneck for the transition towards a fossil independent society. Grid planning is, therefore, facilitated by long-term thinking and transparency between market participants.

A large increase in electricity demand risks putting even greater pressure on the already strained electricity grid. Capacity restraints are problems that arise at the local level, which means that the restraints cannot be predicted based on national estimates of increased electricity demand. Since the national scenarios only predict in what sectors there is a potential for an increase in electricity demand, an analysis is needed with forecasts of electricity demand on the regional level, to understand the local grid situation. According to the authors' knowledge, no published studies exist that show this type of regional analysis up until 2045. Knowledge about the electricity demand, insights and understanding about electricity production and the grid infrastructure within the region is necessary to conduct a regional analysis. This knowledge often includes classified information, which may explain the lack of previous studies.

1.1.1 Aim and research questions

The purpose of the thesis is to contribute with knowledge to grid planning and public debate about how the power system can cope with electrification. Based on the assumption that Sweden will be climate neutral in 2045, the aim is to assess how the electricity demand is predicted to change at the national level and to understand what impact this change would have on a regional level. The thesis studies national scenarios as well as regional conditions. The regional study focuses on the development within the industry, transport, residential and service sectors, as well as the grid operators' thoughts on current and future challenges.

The research questions set to fulfil the aim are:

1. How large is the electricity demand in Sweden projected to be until 2045 with the assumption that climate neutrality will be achieved?
2. In what regions of Sweden will the increase in electricity demand be most significant and how large can the electricity demand become in these regions until 2045?
3. How do the grid operators assess the electricity grid situation to meet a changing electricity demand?
4. What measures are needed to prevent capacity shortages to enable electrification as a decarbonisation route for achieving climate neutrality until 2045?

1.1.2 Scope and delimitations

The thesis focuses on the Swedish transition to becoming CO₂-eq neutral. It is delimited to looking at Swedish conditions and is therefore based on scenarios that forecast the domestic energy demand. The sectors looked at are the industry, transport, and residential & service sectors. The focus is on how high the future electricity demand can become as a consequence of decarbonisation. All information used for the study is non-confidential and is supposed to show what assessments can be conducted with information available for all market participants.

The study is conducted from an electricity demand perspective. Ensuring sufficient electricity production or import of electricity to meet the future electricity demand is not considered. The electricity system is assumed to be completely decarbonised. The thesis is based on three main assumptions:

- Sweden will fulfil the climate goals and be CO₂-eq neutral until 2045.
- Sweden will have economic growth.
- Conversion to climate neutrality will not have a negative impact on competitiveness.

The regional analysis is limited to looking at four Swedish regions.

A delimitation made is that the analyzed scenarios are published in between 2019 and 2020. This delimitation means that the scenarios studied had the possibility to include the most recent information. Older scenarios are used to identify important factors that are believed to impact electricity demand or to identify methods to predict future electricity demand.

2. Climate goals

The Paris agreement was agreed upon 21st December 2015 at the COP21 meeting in Paris by parties of the UNFCCC (UNFCCC, 2020b) and became effective 4th November 2016 (UNFCCC, 2020a). Sweden became a part of the agreement on 12th November 2016 (Prop. 2016/17:146, 2017). The objective of the Paris agreement is to work against the threat of global warming and support those who are affected by climate change. The goal is that the maximum global temperature increase is kept below 2 degrees Celsius, compared to preindustrial levels, but hopefully below 1.5 degrees Celsius (UNFCCC, 2020b). Today, 187 out of 197 parties have ratified the convention (UNFCCC, 2020a).

2.1 Climate goals in European Union

The European Union has set a climate and energy framework until 2030 and a long term strategy until 2050 (European Commission, no date a). During 2019 all EU countries except Poland agreed that the EU should be climate neutral by 2050 (Swedish Climate Policy Council, 2020). The goal until 2030 is to (European Commission, no date a):

- reduce the greenhouse gas emissions with at least 40 % compared to 1990's levels.
- have at least 32 % of renewable energy.
- increase energy efficiency with a minimum of 32.5 %.

GHG emissions are divided into the trading sector (European Commission, 2015) and the non-trading sector (Swedish Climate Policy Council, 2020).

2.1.1 European Emissions Trading System

The European Emissions Trading System (EU ETS) was constructed to limit the amount of GHG emissions that can be emitted in Europe by setting a carbon price (European Commission, no date c). The system has become a vital tool for the EU to reduce the GHG emissions from the trading sector (European Commission, no date c). All EU members, as well as Iceland, Liechtenstein, and Norway, are included in the system (European Commission, no date c). The trading sector includes large-scale industries, power sub-sector and the aviation sub-sector that are operating in EU, which means that the EU ETS covers around 11 000 power stations and industrial plants, as well as aeroplanes operating in between the included countries (European Commission, no date c; Swedish Climate Policy Council, 2020). In total, 45 % of the GHG emissions in the EU are included in the EU ETS (European Commission, no date c).

2.2 Climate goals in Sweden

The Swedish Government has set a goal that Sweden should have net zero emissions of territorial global warming emissions by 2045 and to have negative GHG emissions after 2045 (Prop. 2016/17:146, 2017; Swedish Climate Policy Council, 2019; Swedish Environmental Protection Agency, 2019a). The goal is to reduce GHG emissions with at least 85 % compared to GHG emission rates in 1990 (Swedish Climate Policy Council, 2019; Swedish Environmental Protection Agency, 2019a). The last 15 % can be covered with supplementary measures, e.g., binding of GHG emissions in forest and ground, investing in projects that reduce GHG emissions in other countries or Bio-CCS (Swedish Environmental Protection Agency, 2019a; Swedish Climate Policy Council, 2020). Where there is no suitable solution for decarbonisation, CCS is seen as a possible solution (Prop. 2016/17:146, 2017; Prop. 2019/20:65, 2019). Emissions from international transports and emission and uptake from land use, change in land use, and forestry (LULUCF) are excluded from the 2045 target (Swedish Climate Policy Council, 2019).

GHG emissions in Sweden are divided in the same way as on the EU level, into the trading sector and the non-trading sector. The trading sector in Sweden consists of around 750 industries and energy companies, as well as 12 airway companies that are obliged to follow the EU ETS (Swedish Environmental Protection Agency, 2019f). The trading sector accounted for around 40 % of Sweden's GHG in 2018 (Swedish Environmental Protection Agency, 2019a).

The non-trading sector consists of residential and service, domestic transports, agriculture, and waste management. These accounted for around 60 % of the GHG emissions in Sweden during 2018 (Swedish Environmental Protection Agency, 2019a). To reach the goal until 2045, the government have set milestones to reduce the GHG emissions from the non-trading sector compared to the GHG emissions in 1990 (Prop. 2016/17:146, 2017; Swedish Environmental Protection Agency, 2018, 2019a):

- **2020:** Reduction by 40 % with a maximum of 13 % of supplementary measures.
- **2030:** Reduction by 63 % with a maximum of 8 % of supplementary measures.
 - The government has set a specific goal that the GHG emission from the domestic transport sector shall be 70 % lower by 2030 compared to 2010 (Prop. 2016/17:146, 2017; Swedish Environmental Protection Agency, 2018).
- **2040:** Reduction by 75 % with a maximum of 2 % of supplementary measures.

With today's control means and policies, it is only the goal by 2020 that will be fulfilled, but only by implementing supplementary measures (Swedish Climate Policy Council, 2020).

The Industrial Emissions Directive (IED) is an EU directive that acts as a driving force for decarbonisation in the industry. The directive sets requirements for the industry on environmental protection, reporting, and applying Best Available Techniques (BAT). (European Commission, 2020)

The *Act of reduction of greenhouse gases from fuels by the blending of biofuels in gasoline and diesel fuels (2017:1201)* became valid in 2018 (SFS 2017:1201, 2017). It states that fuel suppliers of gasoline and diesel are obliged to reduce the climate impact from their sold fuel by adding biofuels in the fossil fuel (Swedish Energy Agency, 2019a). The share of biofuels will be higher for each year, and during 2020 the GHG emissions from gasoline need to be reduced by 4.2 % and diesel by 21% (Swedish Energy Agency, 2019a). The Act is seen as one factor in reaching the climate goal set by 2030 for the transport sector (Swedish Energy Agency, 2019a). The targets for 2030 are not set and will be depending on the electrification rate (Swedish Energy Agency, 2020b). The share of biofuels will be adjusted to achieve a reduction of 70 % (Swedish Energy Agency, 2020b).

3. The role of electricity in the Swedish energy system

The Swedish energy system is still heavily reliant on the input of fossil- and nuclear fuel, which accounted for nearly 55 % of the supplied energy during 2017 (Swedish Energy Agency, 2020a). The largest final user of energy is the residential & service sector, using approximately 146 TWh, followed by the industry sector using 143 TWh (Swedish Energy Agency, 2020a). The transport sector is using around 88 TWh (Swedish Energy Agency, 2020a). However, the majority of the energy use in the transport sector is fossil fuels (Swedish Energy Agency, 2020a), meaning that the sector is facing a large transition in order to reach the climate targets. In the government initiative Fossil Free Sweden, the energy industry has undertaken the responsibility to meet electrification in the different sectors through good cooperation between the involved actors on the energy market and by supplying fossil-free electricity with high security of supply (Swedenergy and Fossil Free Sweden, 2020).

3.1 The Swedish electricity market

The electricity market consists of the transmission of electricity and financial trading. Several actors are involved in these two flows. **Figure 2** shows the different actors operating on the market and how they are related (Swedish Energy Markets Inspectorate, 2016).

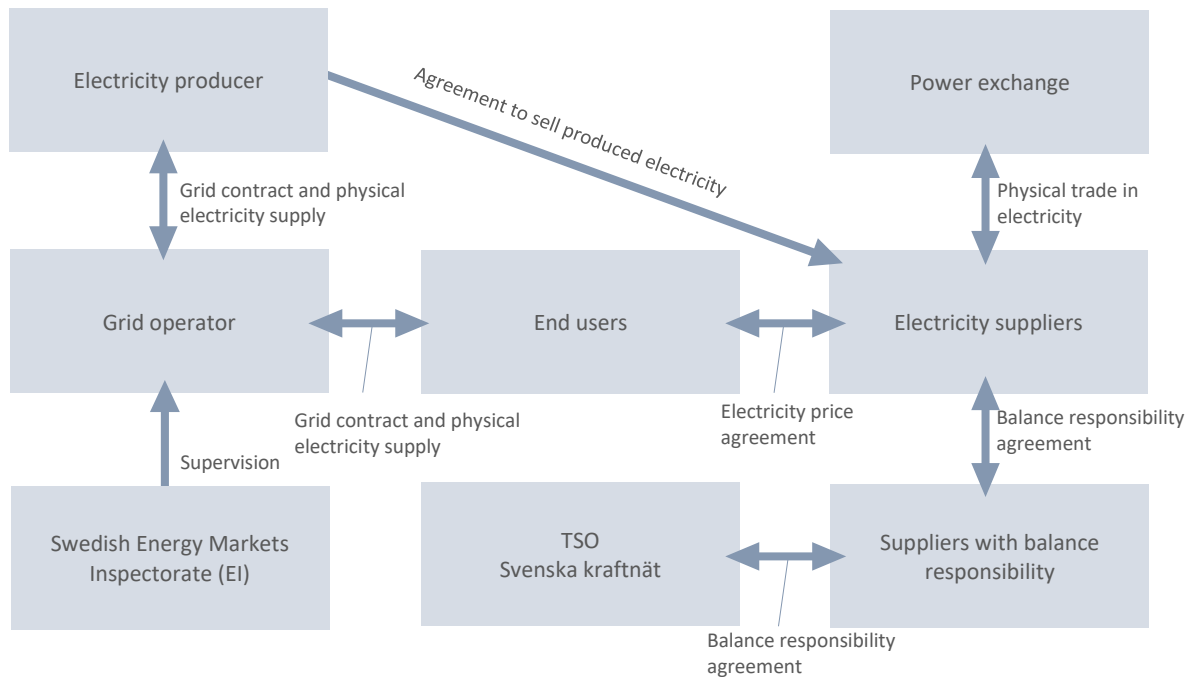


Figure 2: Visualisation of how the electricity market works and which players are involved. Based on information from Swedish Energy Markets Inspectorate (2016)

Grid operators own and operate the electricity grids. Their function is to transmit electricity between where it is produced and where it is used. Around 170 grid operators are operating on the Swedish electricity market. The grid operators need to have the concession to operate grids and to build new grids. These concessions are granted by EI, which is the regulatory authority. Only one grid operators is allowed to operate a grid within the same geographical area, meaning that the electricity grids are becoming natural monopolies. EI, therefore, also has the responsibility to regulate the revenues of the grid operators. (Swedish Energy Markets Inspectorate, 2016)

The electricity producers supply the system with electricity. Producers can be of various sizes, everything between energy companies operating large scale nuclear or hydropower to small PV-systems on residential connected to the grid. (Swedish Energy Markets Inspectorate, 2016)

Electricity suppliers buy electricity on the power exchange and sell to end-users. In order for the electricity system to be in balance, there are electricity suppliers with balance responsibility. On behalf of Svenska kraftnät (Svk), suppliers with balance responsibility are responsible for ensuring that the amount of electricity supplied equals the amount of electricity used in the

system. Svk is the transmission system operator (TSO) and has the overall responsibility for the system. (Swedish Energy Markets Inspectorate, 2016)

3.1.1 Grid

Today's electricity grids are extensive and interconnected with our neighbouring countries, which allows for import and export (Stattnett *et al.*, 2019). Since electricity demand is not always located at the same location as production and trade with neighbouring countries is increasing, the demand for high transmission capacity is growing (Stattnett *et al.*, 2019).

Wiesner *et al.* (2019) explains that the Swedish electricity grids were heavily expanded during the 70's and 80's and were at this time often over-dimensioned. It is further described that the power industry considered the expansions of the grid completed, and during the 90's and 00's, the focus has mainly been on maintenance. Sweden has today one of the oldest transmission grids in the EU, which therefore faces major reinvestment needs (Svenska kraftnät, 2019a). Large reinvestments will also be required in the regional and local grids (Swedenergy and Fossil Free Sweden, 2020). Svk currently have several projects for increasing the grid capacity with investments corresponding to SEK 60 billion before 2029, where 40 % are reinvestments in the current grid, and 60 % are connected to expanding the grid (Svenska kraftnät, 2019a). Some of the projects will continue towards 2040, and the total cost is estimated to around SEK 100 billion (Svenska kraftnät, 2019a).

Reinforcements and expansion of the electricity grids are often associated with long permit processes, which risk preventing a conversion process that is fast enough for the climate goals to be achieved. (Swedenergy and Fossil Free Sweden, 2020)

3.1.1.1 Grid levels

The Swedish electricity grid is divided into three grid levels, the national grid for transmission, as well as regional and local grids for distribution (Svenska kraftnät, 2014). **Figure 3** shows how the electricity system is constructed at different grid levels.

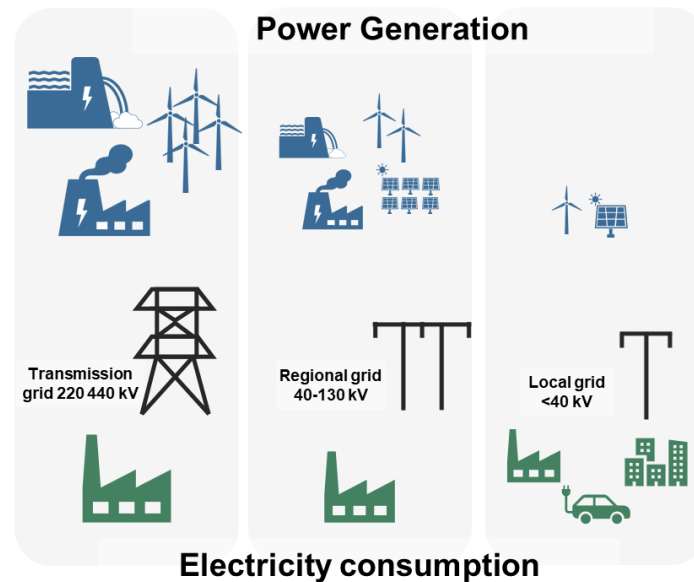


Figure 3: Schematic overview of the electricity system and the different grid levels based on information from Svenska Kraftnät (2014).

The national transmission grid is defined as a coherent grid that extends over several regions, links the national grid with grids in surrounding countries, and has a voltage of at least 220 kV ((1997:857), 1997). The national grid is operated by Svk and consists of 15 000 kilometres of power lines with a voltage between 220 and 400 kV (Svenska kraftnät, 2014). Transformers and switchgear stations are also included in the national grid system (Svenska kraftnät, 2014). Electricity from large production facilities is supplied directly to the national grid. To be connected to the 220 kV, the feed-in capacity need to be at least 100 MW, and to the 400 kV the feed-in capacity need to be at least 300 MW (Nordling, 2016).

The purpose of the regional grid is mainly to be the link between the transmission grid and local grids in cities. The regional grids are interconnected with the national and local grids, local electricity production, such as CHP plants or wind farms, as well as individual users with high electricity consumption (Svenska kraftnät, 2014). Regional grids are defined to have a voltage lower than 220 kV ((1997:857), 1997). The majority of the regional grids are owned and operated by Vattenfall Eldistribution, Ellevio, and E.ON Elnät Sverige (Nordling, 2016).

The local grids connect the regional grids with the end-user. Small-scale production can be fed directly to the local grids, such as private PV-systems. The local networks have the lowest voltage level, between 0.4 kV and 20 kV. There is a large number of different actors who own and operate the country's local grids, and the majority are municipal energy companies. (Nordling, 2016)

The transmission capacity in a powerline is temperature-dependent. The capacity is approximately 20 % higher during winter than during summer due to the cooling effect of winter climate (Pöyrö, 2018).

3.1.1.2 Capacity shortage and power shortage

Capacity shortage in the electricity grid is a problem that mainly occurs on the regional and local grid levels when electricity must be transmitted from where it is produced to where it is to be used (Wiesner *et al.*, 2019). The electricity power demand in Sweden depends on several factors, e.g. time of the day, time of the week, season and where in the country (Nordling, 2016). It is believed that the load curves in the electricity system will change in the future due to the electrification of the transport sector and the installation of heat pumps (Boßmann and Staffell, 2015). Bruce *et al.* (2019) believes that the peak electricity demand will increase from around 26 GW today to around 32 GW in 2045.

As a result of the power demand being so varied, capacity shortages usually occur for a couple of hours (Wiesner *et al.*, 2019). The triggering factor for the risk of capacity shortages may be that new industries are established, and industries or cities expand (Wiesner *et al.*, 2019). There might, therefore, not be enough capacity in the power lines to supply an increased electricity demand. In Sweden, the majority of the electricity is produced in the north, and the electricity demand is highest in the south, which means that the electricity needs to be distributed (Wiesner *et al.*, 2019). Due to this, it is not uncommon that capacity shortages in local areas are caused by the lack of capacity in the transmission grid (Wiesner *et al.*, 2019).

The common underlying reason why capacity shortage occurs in Sweden is that the process for building new grid infrastructure is slower than the process of establishments leading to an increased electricity demand (Svenska kraftnät, 2019a). The electricity grid usually is expanded based on the demand that is believed to be required, which means that there is no significant overcapacity (Svenska kraftnät, 2017b). Over-dimensioned grids are not built since expansions need to be socioeconomically justifiable, which it risks not to be if it is based on speculation (Svenska kraftnät, 2017b). Exceptions to the profitability assessment are made because of the obligation of connection, which means that the electricity grid operators are obliged to connect new producers and consumers on request (Svenska kraftnät, 2019a). Shut down of local production in large city regions has also contributed to the problem of capacity shortage as electricity needs to be transmitted from production facilities further away from where it is to be used (Svenska kraftnät, 2019a). Wiesner *et al.* (2019) showed that the situation with local capacity shortage in the metropolitan areas happened due to lack of communication and coordination between the actors that have the possibility to affect the development of the grid.

Power shortages occur momentarily when not enough electricity is produced or imported to meet the demand, i.e., unbalance in the system (Wiesner *et al.*, 2019). Power shortages can be a problem if the electricity demand suddenly increases a lot or if the shutdown of production plants is needed, for example, because of maintenance (Wiesner *et al.*, 2019). Power shortages are solved

by increasing electricity production or decreasing electricity demand within the system (Wiesner *et al.*, 2019). Boßmann and Staffell (2015) concludes that the electrification of transports or an increased number of heat pumps is likely to result in an increased peak load. When Boßmann and Staffell (2015) studied the German electricity system, they concluded that electrification of one million cars could increase the electricity peak load by 1.5 GW. Increases of this size will make it more challenging to balance supply and demand in the electricity system (Boßmann and Staffell, 2015).

3.1.1.3 Concession for operating electricity grids

A high-voltage electrical power line cannot be built or operated without a permission called grid concession ((1997:857), 1997). The Swedish Energy Markets Inspectorate is the responsible authority for giving concession (Swedish Energy Markets Inspectorate, no date). A grid operator need to be legally separated from companies conducting electricity production or trading in electricity ((1997:857), 1997). This is to ensure that monopoly businesses are separated from companies on a competitive market (Goding *et al.*, 2018). A grid operator company can be part of a business group conducting electricity production or trading in electricity, but management need to be separated and the company operating grids cannot be favoured by other business stakeholders (Goding *et al.*, 2018). Commercially sensitive information or staff must also not be shared between the grid operator company and the other companies in the business group ((1997:857), 1997).

The grid operator holding a concession is responsible for maintenance, operation, and expansions of the grid as well as connecting it with other grids and electricity producers ((1997:857), 1997). There are two types of concession for the grid (SOU 2019:30, 2019; Wiesner *et al.*, 2019):

- Line concession:
 - is used for a single power line with a predetermined distance and location.
 - is often used to expand the transmission and regional grids.
- Area concession:
 - is used for a system of power lines in a specific area. Often used for local grids.
 - has a predetermined allowed maximum voltage.

The permitting process for grid expansions needs long term planning (SOU 2019:30, 2019). An expansion includes getting all the permissions, getting the grid concession approved, and construction of the grid. The time it takes to get grid concessions depends on several factors, the size of the project, type of grid concession, contacts with the landowners, alternative solutions and the environmental impact from the grid (SOU 2019:30, 2019).

According to Svenska Kraftnät (2019), it can take between 10-12 years to build a power line in the transmission grid that requires exploitation of new land. The permit process takes between 5-10 years, and the construction takes between 2-3 years (Svenska kraftnät, 2017a). Even longer lead times are described by Pöyrö (2018), who states that it can take up to 15 years for the expansion of new transmission grids. The lead-time for expanding the regional grid is around five years, nevertheless it can take up to 15 years if complications in the permit process arise (Pöyrö, 2018). Svenska kraftnät (2019a) and the Government offices of Sweden (SOU 2019:30, 2019) states that the concession process needs to be shortened due to the currently strained situation in the grid. Tenggren *et al.* (2016) have identified the involvement of several different courts and agencies as a barrier in the grid expansion process. Since the different court proceedings are conducted independently of each other, a court refusal can lead to the entire concession procedure having to be redone from the beginning (Tenggren *et al.*, 2016).

The process for transmission grid expansions starts with Svenska kraftnät deciding to expand the grid (Svenska kraftnät, 2020). A decision is made based on a grid analysis, socioeconomic calculations, technical studies, and other assessments (Svenska kraftnät, 2020). This is followed by a dialogue between authorities, municipalities, county councils, landowners, and others that have interests in the affected area, to identify the best location for the power line (Svenska kraftnät, 2020). When a location has been decided, Svenska kraftnät apply to the Energy Markets Inspectorate (*Ei*) (Svenska kraftnät, 2020), and it is not uncommon that *Ei* requires that the application need to be supplemented before it is sent out for referral (SOU 2019:30, 2019). The application is then sent out for referral to all stakeholders that are affected by the power line who can appeal against *Ei*'s decision (Svenska kraftnät, 2020). When the dialogues between the actors that will be affected by the line have been held, Svenska kraftnät applies for a concession from the Swedish Energy Markets Inspectorate and all the other permissions that are needed from the county councils, municipalities and other authorities (Svenska kraftnät, 2017c). When the permissions are approved, and the landowners have been compensated economically for the economic loss due to the power line, construction of the line can start (Svenska kraftnät, 2017c).

Tenggren *et al.* (2016) have studied transmission grid development and identified barriers connected to the concession process and its formal complexity. There is a lack of clear guidelines leading to differences in how decision-makers in various regions are working with solving problems. This has resulted in conflicts between different stakeholders, such as municipalities, regional authorities and grid operators, as well as Svenska kraftnät as TSO. One reason to why conflict occurs is that the prioritization of questions regarding, e.g. land-use or local versus global sustainability concerns, is not predefined. These conflicts, often including appeals, tend to prolong the grid expansion process. Tenggren *et al.* (2016) further explains that it is difficult to define the different stakeholders in a concession procedure, meaning that it is an uncertainty in which stakeholder should be included and consulted during the procedure.

4. Decarbonisation and electrification

GHG emissions can be used as an indicator of the sectors in which significant changes will occur, provided that the climate goals will be achieved. The transport sector and the industry sector each stand for around one-third of the national greenhouse gas emissions, see **Figure 4** (Swedish Environmental Protection Agency, 2019d).

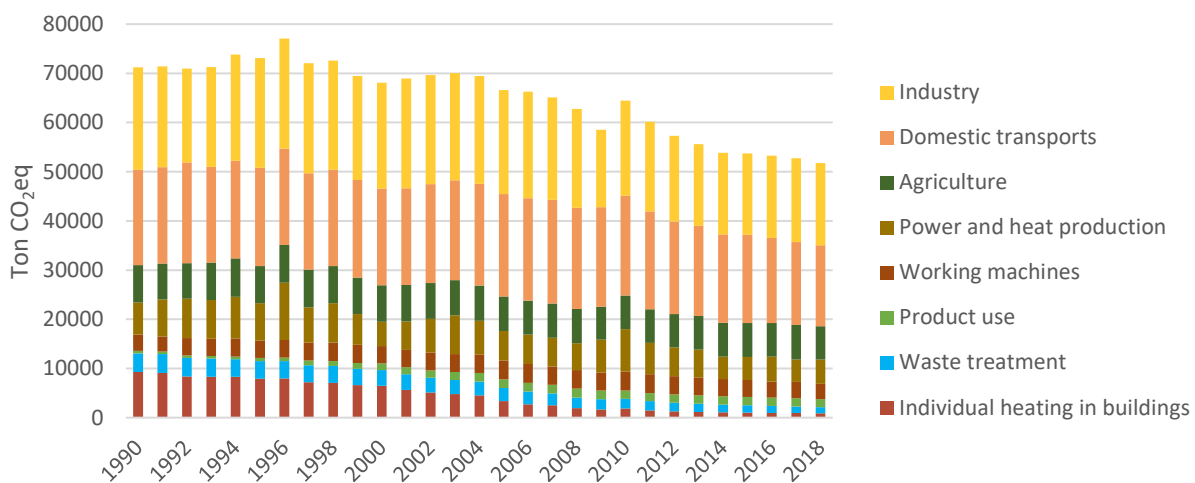


Figure 4: Domestic GHG emissions from industries, transports, residential & service between 1990-2018. Based on data from Naturvårdsverket (2019d)

Domestic emissions amounted to 51.8 million tonnes of CO₂-eq in 2018. The emissions have been reduced by 27 % since 1990, which equals 2 % per year. The reduction of GHG emissions over the past 20 years is mainly connected to the conversion of the heating technique in the residential and service sectors. The industry sector has been able to reduce its emissions by increasing the proportion of biomass, and the transport sector has benefited from more efficient engines and new biofuels. To achieve climate neutrality by 2045 and thereby reach the climate goals, emissions need to be further reduced in all sectors with an average of 5-8 % per year. (Swedish Environmental Protection Agency, 2019a)

4.1 The industry sector

Over 90 % of the GHG emissions in the global industry sector are emitted from 10 industries where the cement, iron & steel, and chemicals & plastics stands for over 55 % (Rissman *et al.*, 2020). These industries are also a large part of the industry sector in Sweden, see **Figure 5**. A considerable reduction in GHG emission can, therefore, be reached by focusing on converting and improving these processes and products (Rissman *et al.*, 2020).

Many researchers have previously studied the challenges facing the industrial sector to become fossil-independent. Rissman *et al.* (2020) conclude that it is possible to reach net-zero emissions in the industry at a global level this century and that it is necessary to decarbonize the global industry sector to reach net-zero emissions between 2050-2070 to fulfil the Paris agreement. Both biomass and electrification with renewable electricity are potential ways to decarbonise the industry sector (Lechtenböhmer *et al.*, 2016; Sandberg *et al.*, 2019). Rissman *et al.* (2020) writes that electrification will have an essential role in decarbonising the industry sector, together with other solutions such as zero-carbon hydrogen and energy efficiency measures. Carbon capture techniques are other measures mentioned in several studies where it is believed to have an essential role in reducing the CO₂-eq emissions (Bui *et al.*, 2018; Luh *et al.*, 2020; Rissman *et al.*, 2020). It is also concluded by Luh *et al.* (2020) that it is counterproductive with the electrification of the industry if the electricity is not produced with low carbon emissions. Sandberg *et al.* (2019) also showed the importance of having a system perspective when looking at measures for decarbonising the Swedish industry. Looking at just one industry risks a suboptimal conversion. Sandberg *et al.* (2019) also say that different industries will have to take different decarbonisation routes meaning that both conversions to biofuels and electrification will be needed. If all industries were to choose the same route, there would be a high risk for extreme prices (Sandberg *et al.*, 2019). Lechtenböhmer *et al.* (2016) have made a "what-if" analysis where they conclude that electrification of the whole base production of basic materials in EU28 will increase from 1 000 TWh today to over 2 500 TWh by 2050. However, the demand can be lowered by implementing biomass. Lechtenböhmer *et al.* (2016) also conclude that the price for CO₂-eq emissions needs to be higher to make the electrification a competitive path.

The Swedish industrial sector accounted for 17 million tonnes of CO₂-eq in 2018, corresponding to around one-third of Sweden's GHG emissions (Swedish Environmental Protection Agency, 2019a). 92 % of the total CO₂-eq emissions in the sector are included in the EU ETS (Swedish Environmental Protection Agency, 2019a). **Figure 5** shows GHG emissions from all different industry types (Swedish Environmental Protection Agency, 2019a). Two thirds of the emissions from the industry sector can be derived to combustion of fossil fuels, one third can be derived to process emissions and around 5 % of the emissions can be derived to diffuse emissions (Swedish Environmental Protection Agency, 2019a).

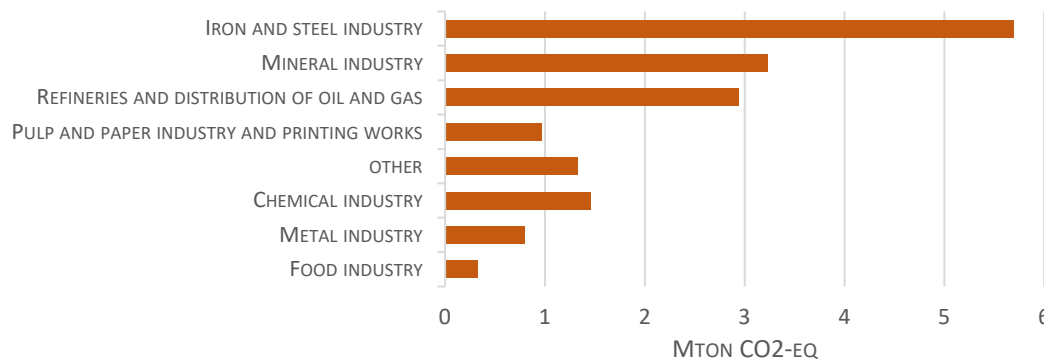


Figure 5: Emitted GHG from different types of industries in Sweden during 2018. Based on data from Naturvårdsverket (2019a).

A large share of the emissions from the industry sector in Sweden can be assigned to a few companies and sites within the basic industry, i.e. industries that are important in the country's economy (Swedish Environmental Protection Agency, 2019b):

- Iron and steel industry
 - SSAB's plants in Luleå and Oxelösund together emit 4.7 million tonnes CO₂-eq annually.
- Mineral industry
 - Cementa AB's factory in Gotland emit 1.7 million tonnes of CO₂-eq annually.
- Refinery industry
 - Preem's refineries in Lysekil and Gothenburg together emit 2.2 million tonnes of CO₂-eq.
 - ST1's refinery in Gothenburg emit 0.5 million tonnes of CO₂-eq annually.
- Chemical industry
 - Borealis AB's site in Stenungsund emit 0.6 million tonnes of CO₂-eq annually.

GHG emissions from the companies and sites described corresponds to 9.7 million tonnes of CO₂-eq and thus close to 60 % of the entire sector's emissions.

The decarbonisation process is at different phases within different energy-intensive industries (Hildingsson *et al.*, 2019). The pulp and paper industry started its decarbonisation during the 1970's and is almost fossil-free today (Hildingsson *et al.*, 2019). In contrast, other industries still are heavily dependent on fossil fuels, such as the iron and steel industry, the mining and mineral industry and the chemical industry (Growth Analysis, 2014; Hildingsson *et al.*, 2019). Policy instruments and energy policies were in combination with the oil crisis crucial for the conversion of the pulp and paper industry (Growth Analysis, 2014).

Lechtenböhmer *et al.* (2016) and Nilsson *et al.* (2017) both concludes that it is technically possible to reach net-zero emissions in the basic industry. However, it comes with a drawback, large investments are needed to replace large technical systems, which leads to increased production costs without increasing the performance of the product (Nilsson *et al.*, 2017). The increased

production cost becomes a problem for the Swedish industry since a large share of the industries compete in a global market (Nilsson *et al.*, 2017). A system perspective is, therefore needed to create a stable energy system with competitive prices (Nilsson *et al.*, 2017). Nilsson *et al.* (2017) also describes that energy efficiency measures often are beneficial for cost reductions and the environment, but the potential for such measures is not high enough to achieve the climate goals.

Investments in new technology are necessary for achieving the climate goals. Rissman *et al.* (2020) has compiled a large number of articles and concludes that it is likely that the technologies are developed and implemented in waves:

Until 2035

- Existing efficiency technologies and demand-side interventions, e.g., increased material efficiency, increased lifespan of products, and re-use, will dominate. Large investments in CCS technologies and zero-carbon hydrogen production will also be required.

2035-2050

- Structural shifts will become more apparent since the technologies are becoming more mature, CCS will be implemented on a large scale, and alternative materials will gain market shares.

Beyond 2050

- Processes that are nascent today, e.g., hydrogen, will be implemented on a large scale.

Investments in research and development, pilot projects, and infrastructure must begin now if this timeline is to be reached (Rissman *et al.*, 2020). Rissman *et al.* (2020) also write that well-developed countries probably will have to implement the new technology earlier than stated in the timeline since the timeframe refers to a global average. Rissman *et al.* (2020) further write that decarbonisation of the industry sector will be facilitated by falling prices for environmentally friendly technology, environmental regulations, and voluntarily climate action.

Nilsson *et al.* (2017) states that Sweden has good prerequisites to take the lead in the transition of the industry due to high climate ambitions both among politicians, in industry, and commerce. The prerequisites are further strengthened with high competence in industries and universities as well as institutional capacity at authorities to manage the conversion (Nilsson *et al.*, 2017).

Roadmaps for decarbonisation of the Swedish industry have been developed as a part of the government initiative Fossil Free Sweden where participating industries commit themselves to show concrete results for work on GHG emission reductions. Two factors that are mentioned in several roadmaps are the need for converting internal transports and that the politicians need to enable both competitive prices and secure access of electricity and bioenergy (Fossil Free Sweden, 2020). shows some of the essential measures mentioned in the roadmaps for the largest industries with the largest GHG emissions.

<p>Cement industry^a</p> <p>Cement will continue to be an important part of the infrastructure, but for the cement industry to be sustainable, fossil-free production will be required.</p> <ul style="list-style-type: none"> - CCS or CCU is needed to eliminate all emissions - Increased usage of biofuels to replace fossil fuels - The long-term plan is to develop technologies that will enable the electrification of thermal processes. E.g., CemZero. 	<p>Refinery industry^c</p> <p>Ambition to have climate-neutral production sites by 2030 and contribute to the transport sector being able to reach the sector-specific climate targets for 2030 and 2045.</p> <ul style="list-style-type: none"> - 10 % of the emissions come from production. Remaining emission occur in the user phase. - Belief in a conversion to biofuels and synthetic fuels and that these will play an important role for long distance-transports, aviation and shipping. - Belief in the development of CCS and CCU.
<p>Mining and mineral industry^b</p> <p>Electrification is seen as the most important part to become fossil-free. Together with the usage of biofuels where electricity cannot be used will make the machines and internal transports fossil-free until 2035.</p> <ul style="list-style-type: none"> - Emission comes from transports, mining, and processing stage. The majority of the emissions are emitted from the production of iron ore pellets, melting of ore into metals, lime, and cement production. - Electrified heating processes can be used in the future but are too immature today and need further research. E.g. HYBRIT and CemZero. 	<p>Steel industry^d</p> <p>Has the ambition to contribute to Sweden achieving the goal of becoming one of the world's first fossil-free welfare nations.</p> <ul style="list-style-type: none"> - 85 % of the emissions come from coal in the reduction process, and the remaining emissions come from fossil fuel use. - Hydrogen Breakthrough Ironmaking Technology (HYBRIT) is a project that aims at decarbonising the processes between pelletising of iron ore to the finished steel product. Currently focusing on replacing the coal with hydrogen in the reduction process of the iron ore. - A need to develop bio coal that can be used for the reduction of iron ore for powder production and in the scrap melting process. - Bio-based gas needs to be developed since all the heat-treatment cannot be replaced.

Figure 6: Summary of roadmaps to achieve fossil-free basic industries. The cement industry is separated as a subsector in the mining and mineral industry. Based on information from following road maps: ^aCementa (2018). ^bSvemin (2018). ^cFossil Free Sweden (2020b). ^dJernkontoret (2018).

Data centres are a relatively new type of industry that can grow significantly. The establishment of data centres have been quicker than expected due to the favourable conditions for the establishment of this type of industry, with cold climate, large share of renewable in electricity and reduced the energy tax for data centres (Wiesner *et al.*, 2019).

4.2 The transport sector

Domestic transports generated 16.4 million tonne CO₂-eq during 2018. That equals around one-third of the GHG emissions in Sweden (IVA, 2019c; Swedish Environmental Protection Agency, 2019c). Road traffic accounts for 88 % of the emissions in the transport sector, of which passenger cars account for around 60 % of the emissions (Swedish Environmental Protection Agency, 2019a). **Figure 7** illustrates the 2018 CO₂-eq emissions from the transport sector during 2018.

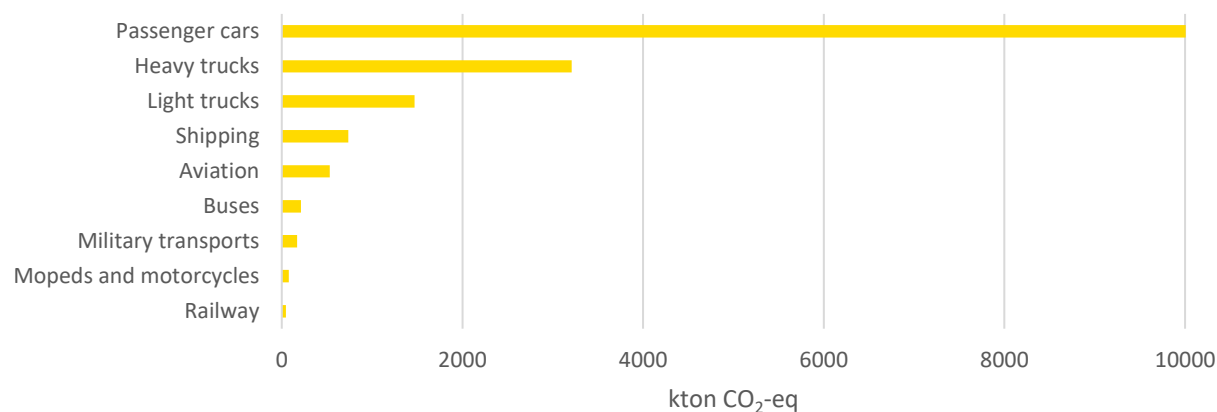


Figure 7: Domestic CO₂-eq emitted divided per type of transport during 2018. Based on data from Naturvårdsverket (2019a).

The final energy use in the Swedish domestic transport sector was 88.2 TWh during 2017 (Swedish Energy Agency, 2020a). **Figure 8** shows the final energy use in the transport sector between 2000 and 2017. The share of fossil fuels has been decreasing, but still stands for 75 % of the total use. The use of biofuels has increased during the last two decades (Swedish Energy Agency, 2020a).

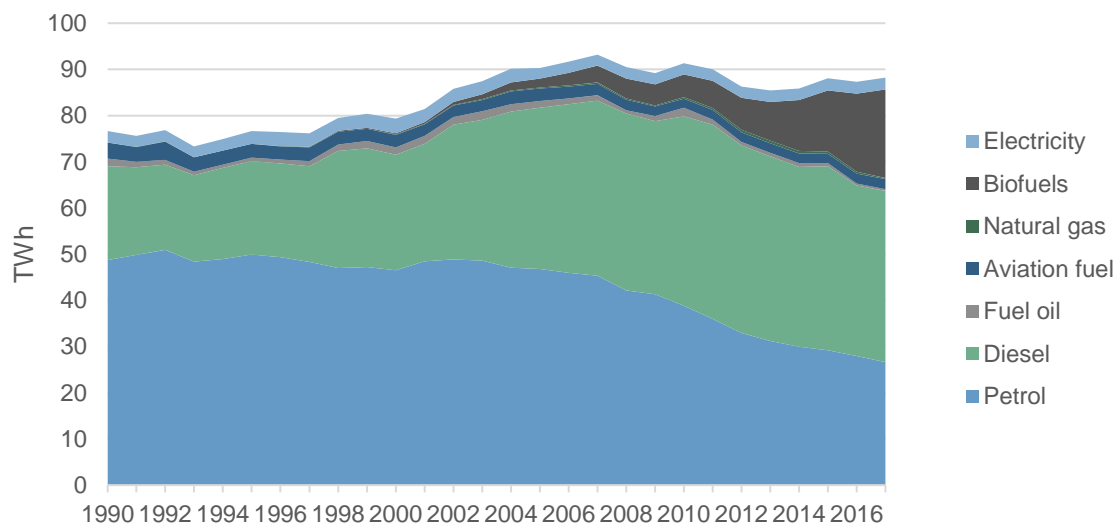


Figure 8: Fuel use within the transport sector between 1990-2017. Based on data from the Swedish Energy Agency (2020a).

Decarbonisation of the transport sector has previously been studied. Van der Zwaan *et al.* (2013) concludes that what energy carriers that the transport sector will shift to depend on regional conditions, such as energy resource availability. Van der Zwaan *et al.* (2013) also concludes that several different energy carriers are likely to be used. Helgeson and Peter (2020) writes about decarbonisation of European road transport and concludes that electrification and the use of synthetic fuels will be necessary, and that synthetic fuels will primarily be necessary for heavy road transports. Helgeson and Peter (2020) estimates that electrification of transports will bring an additional electricity demand of 1 200 TWh at EU level until 2050. Jonkeren *et al.* (2019) writes about freight transports and discusses how decarbonisation would benefit from a transition from road freight to rail and sea freight. Ruhnau *et al.* (2019) writes about road transport decarbonisation and describes that an electrification trend can be seen, but that it is difficult to forecast this trend up until 2050 due to uncertainties in the technology development. Salvucci *et al.* (2019) are analysing decarbonisation of the Scandinavian transport sector, and their analysis shows a demand shift, where road and sea freight is likely to decrease while rail freight is likely to increase due to increased CO₂ tax.

4.2.1 Road transports

Road transport currently accounts for about one-third of Sweden's GHG emissions. As a result, measures for reducing GHG emissions from road transport is vital for Sweden to be able to reach its climate goals by 2045. Kalghatgi (2018) presents different driving forces for the transition towards an oil-independent transport sector:

- Reliable fuel supply and reduce dependence on oil imports.
- Problems with local air pollution, especially in metropolitan areas.
- Concerns and effects of climate change.
- Support domestic agriculture and jobs in rural areas.

The emissions from road transport have a decreasing trend showing a reduction of 22 % between 2010 and 2019, even since the transport work has increased (Swedish Transport Administration, 2020). Transport work is defined as the product of the quantity of people or freight transported and the distance of the transport. The reduction of emissions is explained by the fact that a higher proportion of biofuels and more efficient engines are used today (Swedish Transport Administration, 2020).

Figure 9 shows the number of registered vehicles in Sweden. Passenger cars account for the largest emissions (Swedish Environmental Protection Agency, 2019a) and are also the largest in the number of registered road vehicles (Transport Analysis, 2020a). Emissions from heavy trucks are higher than from light trucks (Swedish Environmental Protection Agency, 2019a). However, the number of registered light trucks is higher than the number of heavy trucks (Transport Analysis, 2020a). Today 4 % of the passenger cars are electric vehicles (Transport Analysis,

2020a). The share of electric busses is 3 %, the share of electric light trucks is approximately 1 %, and the share of heavy electric trucks is negligible (Transport Analysis, 2020a).

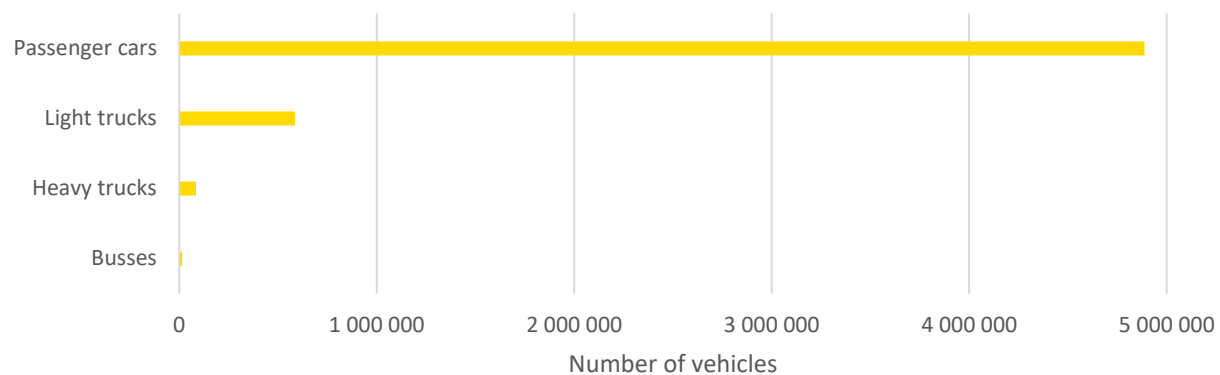


Figure 9: Number of registered vehicles per vehicle type in Sweden in 2019. Based on data from 2019 Transport Analysis (2020a)

Passenger-kilometre from car traffic has increased by 9 % between 2010 and 2019 and is mainly connected to the population growth (Swedish Transport Administration, 2020). The Swedish Transport Administration's forecast for passenger transport shows an annual growth rate of transport work from cars of around 1 % until 2040, corresponding to an increase of 22 % compared to today (Swedish Transport Administration, 2018). After 2040, the growth rate is forecasted to be slowed down to 0.5 % per year (Swedish Transport Administration, 2018).

Tonne-kilometres from heavy trucks have increased by 7 %, and the light trucks have increased by 24 % between 2010 and 2019 (Swedish Transport Administration, 2020). The Swedish Transport Administration is forecasting that transport work from freight transports will continue to increase by 1.8 % per year up until 2040 (Swedish Transport Administration, 2018). The majority of the heavy trucks are loaded and unloaded in the same region (Transport analys, 2019).

Even though the GHG emissions from the transport sector are declining, the development is not fast enough to reach the targets of a 70 % reduction in 2030 (Swedish Climate Policy Council, 2020; Swedish Transport Administration, 2020). The emissions will only be reduced by around 40 % between 2010-2030 with today's economic control means (Swedish Transport Administration, 2020). To be able to reach the target, the yearly reduction needs to increase from today's 2 % to 8 %, which requires new economic control means in the following areas (IVA, 2019c; Swedish Transport Administration, 2020):

- More efficient and electrified vehicles
- Increased share of renewables
- A more transport efficient society

There is an immense interest in electrification within the transport sector, and all the largest vehicle manufacturers are working with this issue. The common belief is that different types of

biofuels, together with electric vehicles, are needed in order to reach the climate targets in 2030 and 2045. According to Kloo and Larsson (2019), it is not sustainable in the long term to transform all transports to biofuels since it is a limited resource and is needed elsewhere. The Swedish Transport Administration has made a potential assessment of the percentage of the vehicle fleet that can be electrified by 2030 and 2045, see **Table 1**.

Table 1: Electrification potential for different vehicle types up until 2045. Source: ÅF (2018).

Year	Passenger cars	Light Trucks	Heavy trucks	City bus
2030	25-30 %	80-90 %	1-3 %	80-90 %
2045	70-85 %	100 %	25-35 %	100 %

Kalghatgi (2018) argues that passenger cars and other types of light vehicles are suitable for electrification but not for heavy vehicles. He believes that the largest problem with electrifying heavy transport is the size of batteries required and the weight it brings. He further explains that today's type of batteries cannot be developed to be much smaller and lighter and that a whole new type of battery technology would be required for new possibilities to arise.

According to Kloo and Larsson (2019), one key factor in the development of the techniques in the transport sector is the infrastructure meaning that biofuels compatible with diesel have an advantage today compared to electrical roads. Kloo and Larsson (2019) categorised heavy transport into local, regional, and national and saw that they have different optimal solutions and timeframe for implementing them. Until 2030 biofuels are the only fuel that can be implemented on a larger scale in the three categories (Kloo and Larsson, 2019). Local heavy transports could convert towards batteries and use a similar technique as the buses by 2030 (Kloo and Larsson, 2019). By 2045 electrical roads can be an alternative for regional and long-distance transports at the high-traffic roads, with the assumptions that control means and policies are supporting the development (Kloo and Larsson, 2019). Regional transports will be able to use a combination of techniques, with batteries, biofuels, and electrical roads (Kloo and Larsson, 2019).

Electric road systems are an alternative solution for converting, primarily, heavy long-distance transports to fossil-free. Börjesson *et al.* (2020) conducted a study in which they investigated the profitability of electrification of a number of trunk road networks in Sweden. The result shows that with today's valuation of CO₂ emissions equivalent to SEK 1.14 per kilo of CO₂, it is socially economically profitable to electrify the trunk roads that link Sweden's major cities, i.e., The E4 between Malmö and Stockholm, the E6 between Malmö and Gothenburg and the National road 40 between Gothenburg and Jönköping. These roads are also highlighted in Sweden's national strategy for freight transport, as prioritised in the government's efforts to facilitate the electrification of freight transport (Ministry of Enterprise and Innovation, 2018). The strategy means that electrification of important freight roads together with supplementary measures such as fast chargers for heavy transport can contribute to efficiency improvements and reduced greenhouse gas emissions from freight transport. According to Kloo and Larsson (2019), over 50 % of the emissions from heavy transports come from 5 % of the government-owned roads

(100 000km). 12 % of the heavy transports are between Malmö and Gothenburg (Kloo and Larsson, 2019).

The study by Börjesson *et al.* (2020) also shows that a transition to fossil-free electricity for heavy transport within the road network of the E4, E6 and the national road 40 could result in an emission reduction for heavy domestic transport by about one-third. The uncertainties are considered to be large regarding the costs of infrastructure and maintenance of electrified roads, as well as the development of alternative solutions such as improved battery technology (Börjesson *et al.*, 2020).

4.2.2 Rail traffic

The Swedish rail traffic system is, to a large extent, electrified and accounts for relatively small GHG emissions. Freight transports corresponded to nearly 24 000 million tonne-km in 2018. Freight by rail is often long-distance, and the most common goods are ore and other products from extraction as well as products from forestry (Transport Analysis, 2019a). There is an even distribution between regional and long-distance passenger transport measured in passenger-km. The total passenger transport work was 13 500 million person kilometres in 2018 (Transport Analysis, 2019a).

Direct emissions from rail transports are 44 000 tonnes per year, which corresponds to about 0.3 % of the GHG emissions in the transport sector (Swedish Environmental Protection Agency, 2019e, 2019a). Transport work for rail transports is forecasted to have a yearly growth rate of 1.4 % up until 2040 (Swedish Transport Administration, 2018). In accordance with Sweden's national freight transport strategy, rail freight should be promoted before road freight, which means that a shift in freight mode can be expected (Ministry of Enterprise and Innovation, 2018).

4.2.3 Shipping

Cargo vessels can transport a large amount of goods long distances with relatively low fuel consumption, which makes it an energy-efficient mode of transport (Swedish Energy Agency, 2017b). In accordance with Sweden's national freight transport strategy, sea freight should be promoted before road freight (Ministry of Enterprise and Innovation, 2018). The Swedish Transport Administration (2018) forecasting that freight transport at sea is the type of freight transport that will increase the most up until 2040, with a yearly increase of 1.9 %.

Domestic transports at sea are included in the climate targets for 2045 and stand for around 4.5 % of GHG emissions within the transport sector (Prop. 2016/17:146, 2017). The GHG emissions for domestic sea transports were 738 000 tonne CO₂-eq in 2018, which is an increase of 63 % since 1990 (Swedish Environmental Protection Agency, 2019d). International shipping is excluded from the climate targets (Prop. 2016/17:146, 2017).

New, more energy-efficient vessels are considered to be an essential part of facilitating a fuel conversion from fossil to renewable in order to change the shipping industry to become fossil-independent (Swedish Energy Agency, 2017b). The Swedish Energy Agency (2017b) believes that it is possible to significantly increase the proportion of biofuels for domestic shipping transports in order to become independent of fossil fuels in the near future. An increased electricity demand may arise in ports as a result of charging hybrid or electrified vessels and ferries (Swedish Energy Agency, 2017b). Shore supply, meaning that a ship's electrical system is connected to the land-based electricity grid when in port, can also lead to large ports getting increased demand for electricity (McCollum *et al.*, 2014; Ministry of Enterprise and Innovation, 2018).

4.2.4 Aviation

GHG emissions from domestic aviation relatively small compared to emissions from road transports. Swedish Transport Administration (2018) forecasts a 0.5 % yearly growth rate of passenger transport work for aviation until 2045. Domestic freight transport by air is minimal compared to other modes of freight transports Swedish Transport Administration (2018), and the air freight that takes place is often carried out by passenger aircraft (Ministry of Enterprise and Innovation, 2018).

The Government is actively working to find ways to promote increased use of biofuels for aviation, for example, by investigating instruments that would promote the use of biofuels (Dir 2018:10, 2018; Ministry of Enterprise and Innovation, 2018). The Swedish Energy Agency is also working on behalf of the government to find ways to increase the use of biofuels in air traffic (Ministry of Enterprise and Innovation, 2018).

4.3 The residential and service sector

The residential and service sector includes energy use from households, service providers, public enterprises, and authorities. The sector stands for close to 40 % of the domestic energy use, and about 50 %, corresponding to 73.4 TWh, of the total domestic electricity consumption. The use of fossil fuels has decreased during the last 30 years, accounting for just over 8 % in 2017 (Swedish Energy Agency, 2020a). One reason for the reduction of fossil fuel use is the conversion from oil to electricity and renewable district heating during the oil crises in the 70's (Di Lucia and Ericsson, 2014; Swedish Energy Agency, 2020a). The electricity consumption in the sector has increased by around 13 % during the last 30 years (Swedish Energy Agency, 2020a).

The final energy use within the sector is primarily electricity and district heating. The annual electricity use can be separated into 30.5 TWh for business electricity, 22.1 TWh for household electricity and 20.8 TWh for electric heating, see **Figure 10**. (Swedish Energy Agency, 2020a)

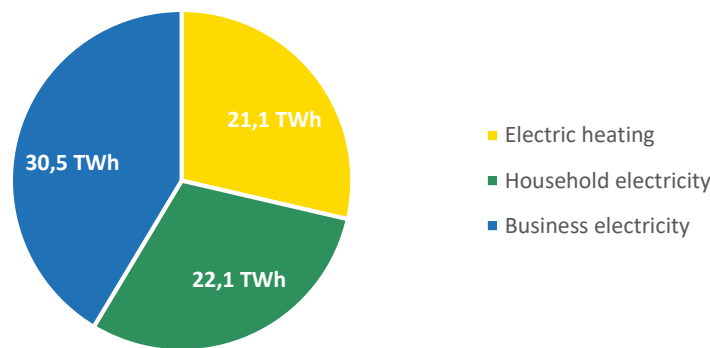


Figure 10: Electricity use within the residential- and service sectors in Sweden during 2017. Based on data from the Swedish Energy Agency (2020a)

The electricity consumption per capita in the residential and service sector can be described as relatively unchanged during the last 30 years, while a more significant decrease can be seen for the total energy use, see **Figure 11**. The unchanged electricity consumption can be explained by that the increase in electricity demand that arises using more electric appliances is taken out by energy efficiency improvements (Swedish Energy Agency, 2017a). According to Wiesner *et al.* (2019), the time when cities have expanded without an increase in electricity demand, is now past. Both local grid owners, municipalities and electricity consumers mentions that the electric power demand is increasing in the cities (Wiesner *et al.*, 2019). The increase is due to the urbanisation in metropolitan areas and the need for new residences in combination with households converting their heating system to heat pumps (Wiesner *et al.*, 2019).

While the electricity consumption per capita has remained about the same, the consumption in relation to GDP has decreased significantly (Statistics Sweden SCB, 2019, 2020), see **Figure 11**. Economic energy intensity is defined by the primary energy use divided by the GDP (Fiorito, 2013).

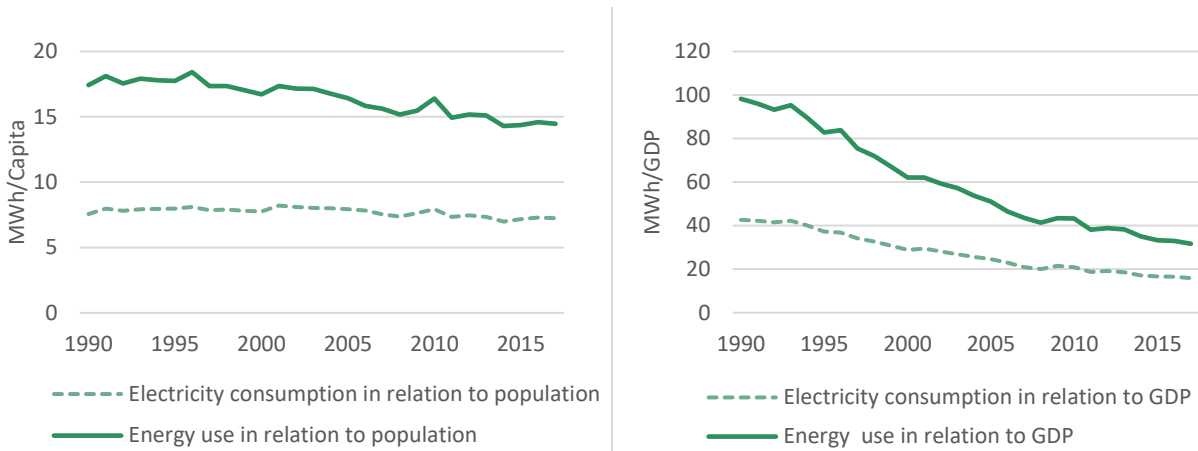


Figure 11: Energy and electricity use in the residential and service sector in relation to population and GDP. Based on data from Statistics Sweden SCB (2019, 2020)

Drivers affecting energy use and electricity consumption within the residential and service sector has been studied by many researchers, mainly with international case studies. Roberts (2008) concludes in a study of UK households that growth in population and number of households is one main factor affecting the future domestic electricity demand. Energy use in Swedish households was studied by Vassileva *et al.* (2012), who concludes that the energy use in a single household can be highly dependent on user behaviour. Climate change is another factor that is connected to the energy use in buildings, mainly in terms of heating and cooling demand. There are large uncertainties in how the energy demand will be affected. However, both Clarke *et al.* (2018) and Andrić *et al.* (2017) states in their articles that the most significant increases in energy demand is most likely to occur in warm countries where the cooling demand will be increased. Andrić *et al.* (2017) also states that the climate changes effects on energy demand for heating and cooling in cold climate countries can be seen as negligible. The results from the study by Andrić *et al.* (2017) also indicated that building renovation measures could have a significantly higher impact on energy demand in buildings than climate changes. A study of energy retrofitting measures in Swedish households by Nik *et al.* (2016) indicates that there is a considerable potential to decrease the energy demand for Sweden's current building stock. However, Nik *et al.* (2016) says that what measure that should be implemented should be preceded by a multi-criteria analysis at the individual building level to determine which measure is most appropriate and to avoid rebound effects. Mata *et al.* (2013) creates a model based on statistically representative buildings to be able to analyse the impact of energy efficiency measures. They conclude that it is possible to reduce the final energy demand, with over 50 %, in the Swedish residential building stock until 2050.

4.4 Technologies for decarbonisation

There are different technologies for decarbonising the sectors. The techniques presented requires electricity and will therefore increase the electricity demand when implemented. Which technologies are being implemented on a large scale may, therefore, have a major impact on the future electricity demand. Technology shifts within the industry often needs to be preceded by research and development. Foster (1986) described that the progress of emerging technologies is often slow and can be anticipated using a so-called s-curve. This method can be used as a tool for company strategists (Asthana, 1995). The pattern of technological development that the s-curve describes is that the progress is initially slow, followed by large-scale implementation over a short period (Foster, 1986). After widely implemented, further improvements often gets too expensive for the rapid technology development to continue (Foster, 1986).

4.4.1 Carbon Capture technologies

Bui *et al.* (2018) writes about implementation of CCS as one of the essential factors for decarbonising the industry sector, in those cases that the emissions cannot be eliminated through other measures, such as a fuel conversion. Carbon capture technologies can be used for capturing CO₂-eq from different type of sources (Rackley, 2017). There are several different technologies for the capture and storage of CO₂ available on the market, but there are also much ongoing research (Rackley, 2017; Bui *et al.*, 2018). Today most of the cost connected to the CCS are the capital costs and not the operational costs (Bui *et al.*, 2018). The captured CO₂ can also be utilized instead of stored, i.e. Carbon capture and use (CCU), to produce finished products, e.g. synthetic fuels, plastics and building materials (Rissman *et al.*, 2020).

IVA (2019b) estimates the electricity demand to be 0.3 MWh per tonne of captured CO₂. According to Bui *et al.* (2018), great progress has been made during the last five years in how to store the CO₂. However, there is still a need for research about the CO₂ storage capacity, the behaviour of the CO₂ in the storage, leak detection and remediation (Bui *et al.*, 2018). Hydrogen production is a possible utilization of captured CO₂, i.e. CCU. The magnitude of CCU is predicted to be very small compared to CCS (Bui *et al.*, 2018).

Bui *et al.* (2018) believe that there are no feasible scenarios to reach the 1.5 °C goal without negative emission technologies (NETs). One of the technologies in this area is *Bioenergy carbon capture storage* BECCS (Bui *et al.*, 2018; Levihn *et al.*, 2019). Using BECCS means that CCS is used where bioenergy is used as input, which results in negative CO₂ emissions (Levihn *et al.*, 2019). NETs are also a possible way for compensating emissions that are difficult to remove, e.g., emissions from shipping and aviation industry (Bui *et al.*, 2018). Levihn *et al.* (2019) showed in a case study of a CHP plant in Sweden that implementation of BECCS would lead to a considerable reduction of CO₂-eq. However, the implementation would lead to significant investment costs and that the profit margin could be reduced by up to 66 % (Levihn *et al.*, 2019).

4.4.2 Hydrogen production technologies

Hydrogen can be produced using different technologies and feedstocks, either fossil, biobased, or water. The majority of the hydrogen is today produced using fossil-based fuels; natural gas stands for 76 % and coal for 23 %. Low carbon hydrogen is believed to have an important role in the future since it can decarbonise sectors where it is hard to reduce the CO₂. Hydrogen has the advantage that it can be used as both energy carrier and raw material within the industry. (IEA, 2019)

Hydrogen can be produced from water through electrolysis (Lechtenböhmer *et al.*, 2016). Rissman *et al.*'s (2020) study show that with current technology, approximately 51 kWh of electricity is required to produce 1 kg of hydrogen. If the entire world's current hydrogen demand were to be covered by hydrogen produced using electrolysis, the electricity demand would be around 3 600 TWh, which is greater than the electricity demand for the entire EU (IEA, 2019).

4.4.3 Heat treatment technologies

A large share of fossil fuel use in the industry sector is used in thermal processes (Rissman *et al.*, 2020). There are different available technologies for supplying heat at various temperatures with electricity instead of fossil fuels.

Examples of advanced technologies that can supply heat in high-temperature ranges are electric arcs and plasma furnaces. Electric heating technologies are often easier to temperature regulate, which usually makes it more energy-efficient than fossil fuel combustion technologies (Lechtenböhmer *et al.*, 2016).

5. Methodology

The thesis work follows three phases based on the problem statement and the different research questions. The different phases are approached with different methods for data collection and analysis described in this chapter. The four research questions can be linked to the thesis phases, as illustrated in **Figure 12**.

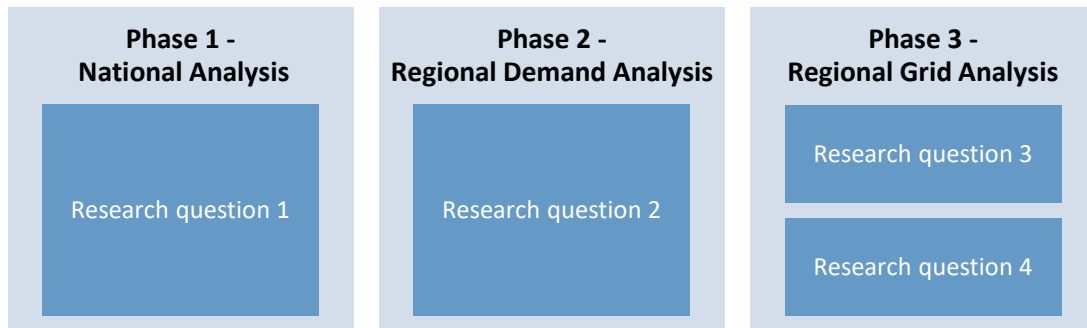


Figure 12: Illustration of how the research questions are linked to the different phases of the thesis.

Phase 1 aims at creating an overview of existing scenarios predicting the future electricity demand up until 2045. The result will show an overview of how different actors believe that the electricity demand will develop and what important assumptions that are included and excluded in each scenario. The overview will also result in the choice of a *Base scenario* used for the other thesis phases.

Phase 2 aims at understanding the underlying reasons why certain regions might risk capacity restraints in the electricity grid. A more detailed analysis needs to be made than is possible by only looking at national scenarios analysed in *Phase 1*. Based on the overview and analysis of existing national scenarios, the aim is, to identify and choose geographical regions where significant changes in electricity demand and limited transmission capacity can occur. An estimate of how the electricity demand can change is after that made for the chosen regions.

Phase 3 aims at investigating the grid situation in the chosen regions. An analysis of the possibilities to meet the potential electrification is made based on the results from *Phase 2*. The result will shed light on what is missing to be able to make better assessments of what measures are needed in the electricity grid in order to maintain high security of supply reliability and, at the same time, be able to meet increased electricity demand.

The three phases are carried out according to the working methodology described in **Figure 13**. The national analysis in *Phase 1* was done independently of the choice of regions in *Phase 2*, which meant that they did not have to be carried out in sequence.

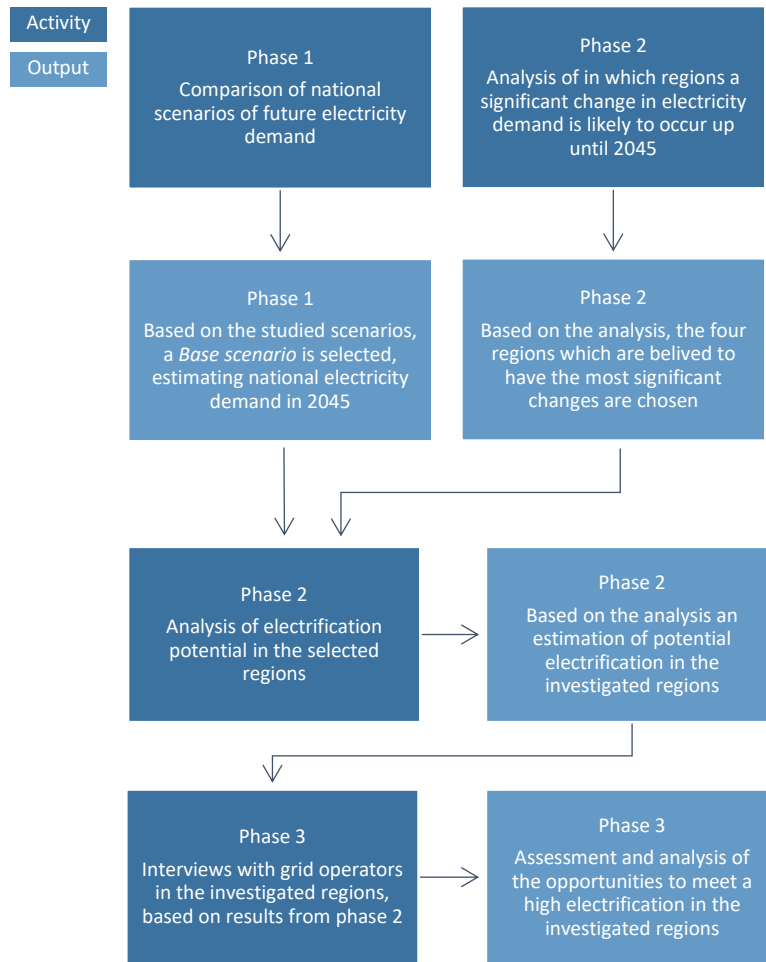


Figure 13: Description of main activities and results produced in each phase.

Kothari (2004) writes about the importance of delimiting the area of research and that it can help guide researchers to make the right priorities. It is further explained that this can be conducted through discussions with colleagues and experts about the problem. Two kinds of interactions were held continuously, adapted to the current state of the thesis work, to help keep the focus of the thesis work relevant and to gain input on which aspects are particularly interesting.

- **Knowledge share session:** Presentation of the current state of thesis and what issues that are faced, followed by discussions together with experts on the issues.
- **Brainstorm session:** Discussion with experts in different fields to identify important areas to dig into deeper.

The majority of the knowledge shares and brainstorm sessions have been conducted with people working within *Strategy & Business Development* which is a part of the staff function *Strategic competence* at Vattenfall AB. Knowledge share sessions have also been conducted with people within R&D working with decarbonisation of industries and development of the transport sector.

5.1 Literature review

A literature review is suitable for describing previous research and highlighting the relevance of the research questions, and the thesis contributes to previous research (Cresswell John, 2014). A literature review is, therefore, conducted to investigate previous studies and research, where the focus guiding the literature review is based on the following:

- Strategies for Sweden to reach its climate targets in 2045
- Electrical grid development
- Predicted technology shifts for decarbonisation in different sectors

Literature has been identified using a systematic literature search, where different search terms have been tested. Agger *et al.* (2017) writes that this often is an iterative process where different terms need to be tested before a good search result is obtained. Citation searching was also conducted in order to obtain additional previous research that the systematic literature search did not cover. An article that is identified as relevant is likely to include more relevant references, and these can, therefore, be used to deepen the literature search (Agger *et al.*, 2017). The online database Web of Science has been the main source for finding scientific literature. The filters were set on all types of documents released between 1975- May 2020.

- Previous research about the industry sector was found by using the search terms; "Industry" Or "Industries" And "Decarbonisation" And "Electrification". The search resulted in 28 articles, of which five were selected to describe the previous research. Rissman *et al.*'s. (2020) article on technologies and policies to decarbonize the global industry was used for further citation searching.
- Previous research about the transport sector and how to decarbonise was found by using the search terms; "Decarbonization" And "Transport Sector" And "Europe". The search resulted in 25 articles, of which five were selected to describe previous research within the field.
- Previous research about energy use within the residential and service sector was found through citation searching starting from an article written by Andrić *et al.* (2017). The article by Andrić *et al.* was found using the search terms; "buildings" And "climate change" And "renovation" And "heat demand" Or "Energy demand". The search resulted in 22 articles, where the article by Andrić *et al.* (2017) was considered relevant for the literature review.

Literature published by different interest organisations and government organisations in the various sectors has been used together with scientific literature in order to build a literature base for the different research questions. The literature consists of scenarios published by actors and organisations within the energy field. The scenarios show predictions of how the energy demand can change up until 2030-2050. Scenarios have been identified and selected with help from the authors' network at Vattenfall AB. Literature from professional organisations, as well as

authorities and government offices, are used for understanding targets for reaching the 2045 climate goals and how the transition is planned to take place in different sectors.

Scientific literature is used to find connections between electricity demand and different types of changes in the society. It is thus an essential part of the method for allocating electricity demand at the regional level, and as a basis for a discussion. Statistics used for describing the current and historical data are collected mainly from Statistics Sweden (no date) and the Swedish Environmental Protection Agency (no date).

5.2 Qualitative data collection

Qualitative research aims to help with understanding the research questions asked by the researcher (Cresswell John, 2014). Participants used as sources for data collection in qualitative research should, therefore, be carefully selected and of relevance to the question studied (Cresswell John, 2014).

Semi-structured interviews were held as part of the data collection in *Phase 2* and *Phase 3*. Semi-structured interviews are following a predefined theme or some prepared questions that need to be covered (Kuada, 2012). The order of the questions can be varied, and the semi-structured interview also allows follow up questions (Kuada, 2012). Saunders *et al.* (2007) described data collected through semi-structured interviews as *“these data are likely to be used not only to reveal and understand the ‘what’ and the ‘how’ but also to place more emphasis on exploring the ‘why’”* which is why it is an interview structure suitable for answering research question 2 and 3.

5.3 Phase 1 – National analysis

In *Phase 1*, an analysis is conducted of how high the national domestic electricity demand may become if the climate targets are to be achieved at the national level. The analyse is done by identifying different scenarios of future electricity demand published between 2019 and 2020, which provides the most up-to-date comparison possible. Five scenarios have been identified as suitable for the national analysis.

The scenarios studied are compared and analysed to understand which assumptions result in significant differences between the scenarios. A decision model based on factors impacting the future electricity demand is constructed to show strengths and weaknesses in the studied scenarios. Factors have been identified during the analysis of the scenarios, in background research, and discussion with supervisors at Vattenfall AB. The decision model for choosing the base scenario is shown in **Table 2**.

Table 2: Decision model used to assess the assumptions in the studied scenarios.

Main assumptions in thesis	Climate goals	Clearly states that the scenario is made with the assumption that Sweden will achieve climate neutrality in 2045.	Takes climate goals into account but does not clearly state that the scenario is made with the assumption that Sweden will achieve climate neutrality in 2045.	Does not state any information on whether the scenario was made with the assumption that Sweden will achieve climate neutrality in 2045 or not. Alternatively, state that the scenario does not take the 2045 climate goals into account.
	Competitiveness	Clearly stated that the scenario is based on the fact that the industry will continue to be competitive, in terms of access to energy at competitive prices.	There are indications that the scenario is based on the fact that the industry will not continue to be competitive,	Clearly stated that the scenario is based on the fact that the industry will not continue to be competitive,
	Economic growth	Is transparent in how economic growth is handled in the scenario and how it is affecting the result.	Is transparent in how economic growth is handled in the scenario but are not transparent in how it is affecting the result.	Do not mention economic growth.
Factors that have a significant impact on forecasted electricity demand	Energy efficiency measures	Transparently states how they manage and implement energy efficiency improvements in the scenario	Describes that energy efficiency improvements are taken into account, but not how they are handled and implemented in the scenario.	Does not mention energy efficiency improvements and whether it is included in the scenario.
	New type of industries	Includes the establishment of new types of industries and describes what these are and what impact they have on the forecasted electricity demand.	Describes potential new industries but does not include them in the scenario	Do not take the establishment of new type of industries into account.
	Population growth	Includes population growth and is transparent in what growth is assumed and what impact it will have on the forecasted electricity demand.	Includes population growth but is not transparent in what growth is assumed and what impact it will have on the forecasted electricity demand.	Does not include population growth

The scenario which is best considered to fulfil the main assumptions of the thesis and give an in-depth description of how the electricity demand is predicted to develop within different sectors, i.e. the scenario that fulfils most green criteria's, is chosen to be the reference for the other thesis phases. If several scenarios have the same number of factors categorised as green, the number of fulfilled main assumptions is the deciding factor. The chosen scenario is referred to as the *Base scenario*.

5.4 Phase 2 – Regional Demand Analysis

Phase 2 is supposed to predict how the electricity demand can change at the regional level up until 2045. The *Base scenario* is used to identify what factors to look into when analysing the different regions. The factors that have been investigated and shown to have a significant impact on the electricity demand at the national level are also the factors used for the regional analysis.

5.4.1 Choice of regions

The thesis is limited to examining four regions selected depending on where the most significant changes in electricity demand are believed to occur to decarbonise the sectors. The assessment is made based on indicators for changing electricity demand for the *industry, transport, and residential and service* sectors. The regional breakdown used for the selection is based on the EU NUTS 3 classification at the county level with 21 counties.

Industry sector: the assessment is based on point source emissions from industry sites within the EU ETS system (Swedish Environmental Protection Agency, 2019b). Emissions within each region have been summarized to illustrate where major decarbonisation will have to take place by 2045 in order to reach the climate targets. Decarbonisation can be achieved either by replacing fossil fuels with bio-based alternatives or electrification of the processes and thereby increase the electricity demand in the region.

Transport sector: the assessment is based on the volume of fossil fuel sold for transports within each region (Swedish Energy Agency, 2020c). The fossil fuels will need to be replaced with renewable fuels or electrified transports, which therefore indicates where increased demand for electricity possibly will occur.

Residential and service sector: the assessment is based on yearly projected population growth between 2020 - 2045 at the regional level as well as at the municipal level to include more local changes. (Swedish Agency for Economic and Regional Growth, 2018). Swedish Agency for Economic and Regional Growth (2018) have forecasted a growth rate per region between 2015-2040. The growth rate is assumed to be the same until 2045. An increased population is believed to lead to an increased demand for electricity linked to the population's activities.

5.4.2 Regional analysis of electricity demand

A regional estimate of future electricity demand is conducted by looking at predicted development in the three sectors and how these are represented in the investigated regions. The scope of the regional investigation is based on what is assumed to be important in the *Base Scenario*. A discussion is held about the possibilities for more extensive electrification than covered by the scope of the base scenario.

The results showing identified electrification potential in the different sectors for each investigated region are compiled and compared with each other. An analysis of the size of the

identified electrification potential compared to current electricity use at the municipal level is made. The calculation is based on Statistics Sweden's reported electricity use at the municipal level (SCB, 2019). An average is calculated for each municipality between 2009-2018.

5.4.2.1 Industry sector

The increased electricity demand in the industry sector is estimated based on how industries state that they are planning to decarbonize their industries. The industries investigated are chosen based on GHG emissions reported within the EU ETS. Limits to exclude smaller industries and to get an analysis basis containing industries believed to have a large electrification potential have been set through iterations.

1. All sites that account for more than 40 000 tonne CO₂-eq in the region are chosen for further studies. These studies consists of investigating if and how they plan to change their processes to become fossil-free. Point emissions from the following sites are omitted:
 - Heat- and power production is assumed to convert to biomass.
 - Sites that accounts for less than 40 000 tonne of the regional GHG emissions are neglected.
 - Sites that accounts for less than 2 % of the regional GHG emissions are neglected.
2. Electricity demand is estimated for the chosen sites based on:
 - interviews with representatives from different industries.
 - information given by the studied scenarios.
 - roadmaps for different sectors and industries describing the predicted development and new technology relevant to the different sectors and industries.

Information from the industries come from representatives working with strategic business development or energy issues within the investigated industries. Information from the industries were gathered in different ways, depending on how the respondent preferred to answer the questions. Most interviews were conducted in video calls where the respondents had access to the questions in advance. Some respondents also chose to answer the questions over the phone or by e-mail. The intention was to get personal contact with all investigated industries, where 14 out of 17 accepted an interview.

The interviews with the different industries covered questions about what:

- processes that the interviewed industry needs to decarbonise in order to reach the climate targets.
- possible solutions the interviewed industry has for decarbonising its processes.
- types of challenges a conversion of the processes would bring.

Notes were taken during the interviews and afterwards compiled as interview summaries supplemented with literature findings and calculations required to estimate the electrification

potential within each industry. All respondents were allowed to read through and correct the compiled material after the interview. A more detailed description of the questions covered during the interviews with the industries can be found in Appendix A1.

Depending on the answers from the interviews, either a predicted electricity demand were given, or it needed to be calculated based on assumptions made by the authors. It is assumed that industry with continuous operation has 8 000 operating hours per year if no other information is obtained. The assumption is used to convert annual electricity demands into electrical power. CCS is assumed to be implemented when other decarbonisation measures do not exist. In accordance with IVA, CCS is assumed to require 0.3 MWh per tonne of captured CO₂ (IVA, 2019b).

5.4.2.2 Transport sector

The transport sector is divided into road transport, railroad, aviation and shipping. Aviation and shipping transports are excluded in this thesis because only a minor share of these transports are domestic meaning that the majority of these transports are excluded in the national climate targets. Other studies also state that there are great uncertainties about these modes of transport, and that a large share of them are more likely to convert to biofuels (McCollum *et al.*, 2014; IVA, 2019c; Sweco, 2020).

A methodology for estimating the electricity demand for road transports in 2030 and 2045 has been developed. Road transport vehicles are separated into passenger cars, light trucks, heavy trucks and intercity buses used as public transports. **Table 3** shows which factors are included in the calculations for estimating electricity demand for the different types of vehicles.

Table 3: Definition of variables and constants used to calculate electricity demand within the transport sector.

$X_{v,r}$ Number of registered vehicles of type v in region r	Based on statistics showing the number of registered vehicles per type and region in year-end 2019 (Transport Analysis, 2020a).
$\bar{D}_{v,r}$ Average driving distance for vehicle type v in region r [km/year]	Based on statistics showing average driving distance per vehicle type and region (Transport Analysis and SCB, 2019).
\bar{E}_v Average electricity demand for vehicle type v [kwh/km]	Based on results from a study conducted by Taljegard <i>et al.</i> , (no date) giving an assumption of electricity consumption per km per type of vehicle. Passenger cars and light trucks are assumed to be static charging. Heavy trucks and buses are assumed to use electric road systems.
$n_{transport\ work,i}$ Increase in passenger or freight transport work until year i [%]	Based on forecasted yearly increase of passenger and freight transport work at national level (Swedish Transport Administration, 2018).
A_v Potential share of electrification for vehicle type v [%]	Based on the potential assessment of the degree of electrification for different types of vehicles at the national level (Johansson <i>et al.</i> , 2018). Electrification rate is assumed to be the same in all regions.
B_r Share of freight loaded and unloaded within region r [%]	Based on the statics of share of freight transports that are loaded and unloaded within the same region (Transport analys, 2019).
P_r Offered public transport in region r - buses [km/year]	Statistics showing public bus transports offered, per region (Transport Analysis, 2019b).

Regional electricity demand for passenger cars is calculated, taking into account regional population changes as growth factor:

$$E_{tot.cars} = x^*_{i,r} \cdot \bar{D}_{cars,r} \cdot \bar{E}_{cars} \cdot A_{cars}$$

where $x^*_{i,r}$ is the estimated number of passenger cars year i in region r . The factor is based on registered passenger cars per inhabitant today in region r and regional population growth estimated by Swedish Agency for Economic and Regional Growth for the year i (Swedish Agency for Economic and Regional Growth, 2018). The average number of passenger cars in relation to population is assumed to stay constant. Regional change in population can thereby be used to estimate the number of vehicles in the region up until 2045:

$$x^*_{i,r} = (\text{Today's average number of cars per inhabitant in region } r) \cdot (\text{estimated population in region } r \text{ in year } i)$$

Regional electricity demand for light trucks is calculated, taking into account yearly national increase in freight transport work as growth factor:

$$E_{tot.l.trucks} = X_{l.trucks,r} \cdot \bar{D}_{l.trucks,r} \cdot n_{freight,i} \cdot \bar{E}_{l.truck} \cdot A_{l.trucks}$$

Regional electricity demand for heavy trucks is based on freight transports loaded and unloaded within the region. Yearly national increase in freight transport work is included as growth factor:

$$E_{tot.h.trucks} = X_{h.trucks,r} \cdot \bar{D}_{h.trucks,r} \cdot \bar{E}_{h.truck} \cdot n_{freight,i} \cdot A_{h.trucks} \cdot B_r$$

Regional electricity demand for intercity buses are calculated based on today's driven distances estimated increase in passenger transport work:

$$E_{tot.buses} = P_r \cdot \bar{E}_{bus} \cdot n_{passenger,i} \cdot A_{buses}$$

For road transports, a comparison is made between the electricity demand for the estimated electrification potential and 100 % electrification of the vehicle fleet.

Increased utilization rate for both passenger and freight transport are considered to be the major drivers for increased electricity demand for rail traffic. Regional statistics and regional forecasts for the development of rail traffic do not exist (Transport Analysis, 2020b). The method for estimating the regional electricity demand for rail traffic is therefore based on the assumption that rail traffic will increase most in areas with a large population. The predicted increase given by the chosen *Base Scenario* is therefore allocated based on regional population size in 2045.

5.4.2.3 Residential and service sector

The electricity demand within the residential and service sector is estimated based on the forecasted population change until 2045. Population growth is calculated based on the Swedish Agency for Economic and Regional Growth's (2018) estimation of annual population growth at the regional level. The regional electricity demand per capita for residential and service sector is assumed to be constant. The electricity demand, E [GWh], for residential and service in region r by year i is calculated by:

$$E_{r,i} = E_{r,current} \cdot (\text{Estimated change in population in region } r \text{ until year } i \text{ [\%]})$$

Allocation based on population growth is motivated by several research articles as well as scenario reports, stating this to be one of the key drivers for increased electricity demand within the sector (Roberts, 2008; Rosenberg *et al.*, 2013; Rydén *et al.*, 2015; Yamagata *et al.*, 2015; IVA, 2019a). Population growth can also be seen as a driver for regional and local growth within the service subsector because it determines where local services such as schools, health care, and stores are located (Swedish Agency for Economic and Regional Growth, 2018).

5.5 Phase 3 – Regional Grid Analysis

Semi-structured interviews are conducted with grid operators operating the grids in the investigated regions. The purpose of Phase 3 is to describe how strained the electricity grid situation in the investigated regions is today, and how good the opportunities are for meeting an electrification.

Interviews were conducted with grid operator representatives working with grid planning or strategic business development. Eight interviews were held with representatives from a total of five different grid operators, see **Table 4**. The selection of interviewed operators consists of the TSO, the largest regional grid operators in each region, and Göteborg Energi, as a company that operates local grid in an area where major changes in all three sectors are predicted.

Table 4: Overview of interviewed companies and what region each interview has been focused on.

Interview	Company	Region	Denomination
(Edfast, 2020)	Svenska Kraftnät	National	Svk
(Brunge, 2020)	Svenska Kraftnät	National	Svk
(Vattenfall Eldistribution AB, 2020b)	Vattenfall Eldistribution AB	Västra Götaland	Vattenfall
(Vattenfall Eldistribution AB, 2020c)	Vattenfall Eldistribution AB	Norrbottn	Vattenfall
(Vattenfall Eldistribution AB, 2020a)	Vattenfall Eldistribution AB	Stockholm	Vattenfall
(Andersson, 2020)	Göteborg Energi AB	Västra Götaland	Göteborg Energi
(Thelin, 2020)	E.ON	Skåne	E.ON
(Öresundskraft AB, 2020)	Öresundskraft AB	Skåne	Öresundskraft

The interviews covered questions about:

- the current grid situation and how the grid operators assess the possibility of meeting an increased electricity demand in the investigated regions.
- what the underlying reasons to why capacity shortage occur are.
- how to prevent capacity shortages.

The questions were sent out together with the result from Phase 2 to the respondents before the interview. The interviews were held via personal video meetings. During the interview, notes were taken and afterwards compiled as interview summaries. All respondents were allowed to read through and correct the compiled material after the interview. A more detailed description of the questions covered during the interviews with the grid operators can be found in Appendix B1.

6. Results and analysis

The results are presented for each phase with subsequent analysis. Results from the *National analysis* is presented in chapter 6.1 and the results from the *Regional analysis* is presented in chapter 6.2. The results from the *Grid analysis* with key findings from interviews with the grid operators is presented in chapter 6.3.

6.1 Phase 1 - National analysis

The results of the *National analysis* consist of a comparison between the forecasted electricity demands in the five studied scenarios, presented in **Table 5**.

Table 5: Information about the scenarios analysed in the national analysis.

Scenario	Publication year	Author/client	Abbreviation
Så når Sverige klimatmålen – Syntesrapport för IVA ^a	2020	IVA - Representatives from all sectors.	IVA
Långsiktig marknadsanalys 2018 – Långtidsscenarier för elsystemets utveckling fram till år 2040 ^b	2019	Svenska Kraftnät	SVK
Färdplan fossilfri el – analysunderlag ^c	2019	NEPP/Swedenergy	Swedenergy
Scenarier över Sveriges energisystem 2018 ^d	2019	Swedish Energy Agency	SEA (1)
En studie av elanvändningens utveckling per län till år 2030 ^e	2020	SWECO/Swedish Energy Agency	SEA (2)

^a(IVA, 2020).^b(Svenska kraftnät, 2019b).^c(Bruce et al., 2019).^d(Swedish Energy Agency, 2019b). ^e(Sweco, 2020)

6.1.1 Comparison of scenarios

A comparison of the possible development for the future Swedish national electricity demand in the studied scenarios are shown in **Figure 14**. The comparison between the scenarios show a spread of 30 TWh at 2045 in the predictions. The IVA scenario predicts the highest electricity demand in 2045 with 207 TWh/y. The other scenarios are estimating relatively similar demands, but lower than IVA.

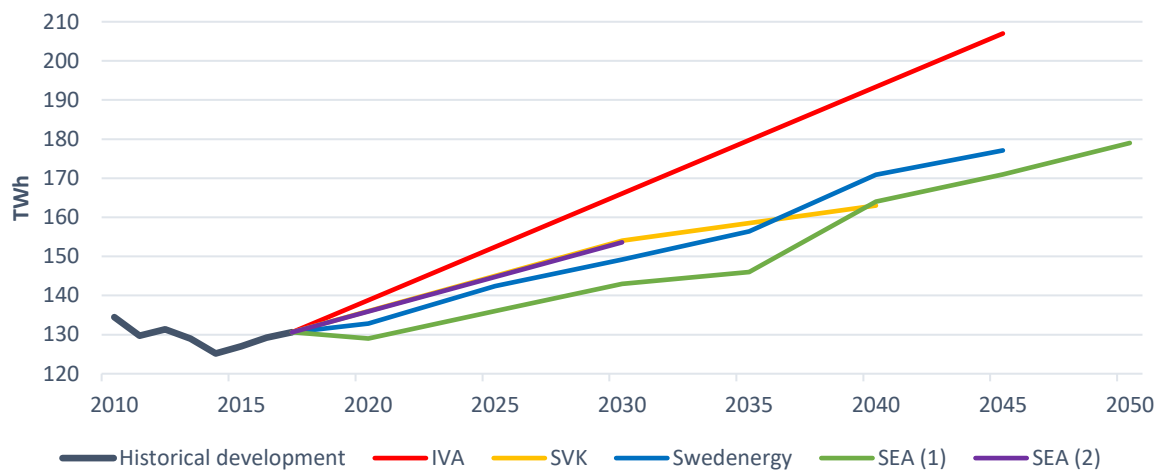


Figure 14: Comparison of the studied scenario's estimated national electricity demand.

Figure 15 shows the predicted electricity demand in the industry sector for the chosen scenarios. IVA is predicting the highest electricity demand in the industry with 102 TWh in 2045, meaning an increase of 52 TWh compared to 2017. Similar to the forecasted national demand illustrated in **Figure 14**, the other scenarios' forecasts on the industry are relatively similar, but lower than IVA.

The estimated increase is mainly due to the implementation of new types of technology to phase out fossil fuels. The IVA base scenario sees CCS and CCU as necessary for reaching the 2045 climate goals and therefore believes in a large-scale implementation. These are electricity-intensive processes, and IVA, therefore, predicts an increased demand of approximately 25 TWh due to these measures. The measures include electricity for hydrogen production used in the CCU process where CO₂ is upgraded to methanol. SVK gives no information about CCS and SEA (1) presents a conservative approach to CCS due to large uncertainties. IVA, Swedenergy and SEA (1) also includes 15 TWh of increased demand due to hydrogen production needed for the HYBRIT project.

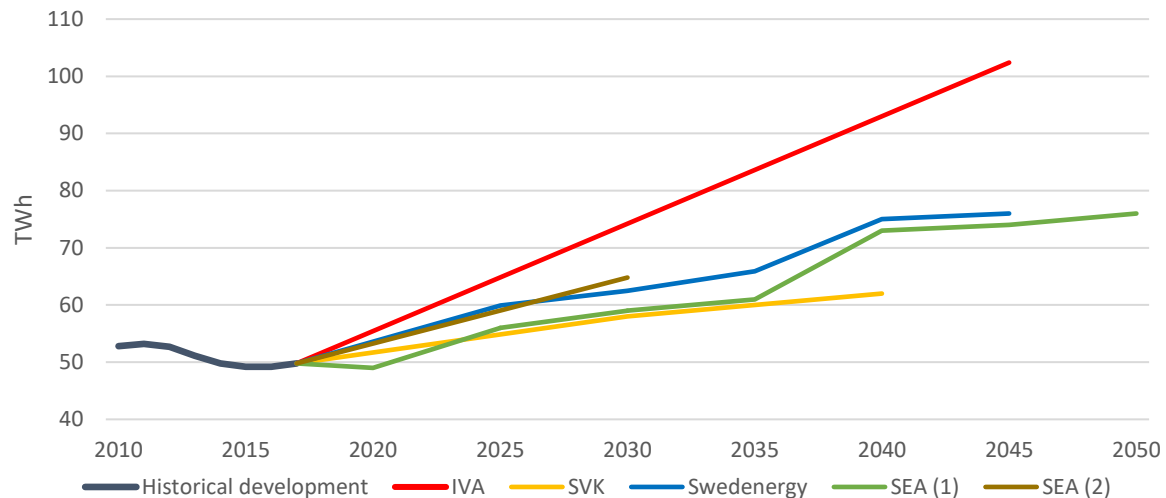


Figure 15: Comparison of the studied scenario's estimated national electricity demand in the industry sector.

IVA predicts that electricity demand from the transport sector will increase from today's 2.6 TWh by 5-10 TWh between 2020 and 2030 where 4-6 TWh are allocated to passenger cars and 4 TWh to heavy transports and busses. An additional increase of 10-15 TWh is predicted between 2030-2045. The total electricity demand will therefore be 25 TWh. In order to reach the transport goal in 2030, IVA believes in high implementation of biofuels for light vehicles up until 2030. Electrification of light vehicles is believed to occur at a higher rate beyond 2030, freeing biofuels for heavy vehicles. The increased demand is mainly due to the electrification of road transports and rail traffic.

SVK believes that electric cars will lead to 9 TWh of increased demand for electricity in 2040. Changes in electricity demand for other transports are assumed to be compensated by energy efficiency measures within all sectors, resulting in a net-zero increase. A prediction for other transports is therefore not separately reported.

Swedenergy believes that electrification in the transport sector will lead to a demand of 7 TWh until 2030 and 19.3 TWh until 2045. It is believed that 20 % of all passenger cars are electrified by 2030 and 70 % by 2045. The scenario also believes in high electrification of distribution trucks and public transport, 80 % by 2030 and close to 100 % in 2045.

SEA (1) is forecasting that the demand will be 6.8 TWh in 2030 and 17.8 TWh in 2045. The increase is due to increased transport work from road and rail traffic transports. SEA (1) believes that 20 % of the passenger cars will be electric or plug-in hybrid vehicles by 2030, and by 2050 the share will increase to 70 %. SEA (2) believes that the electricity demand can increase with 8 TWh until 2030, which equals to a total energy demand of 10.6 TWh.

Figure 16 shows the predicted electricity demand in the transport sector where all scenarios predict an increase in electricity demand.

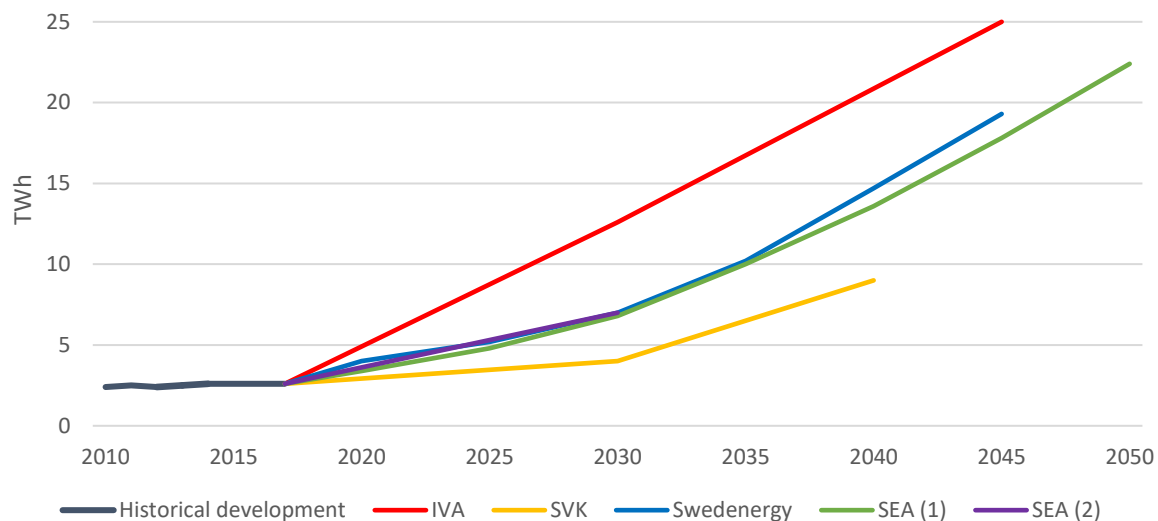


Figure 16: Comparison of the studied scenario's estimated national electricity demand in the transport sector.

Figure 17 shows the forecasted electricity demand in the residential and service sector. The predicted increase in this sector is moderate in comparison with the other two sectors. The highest predicted increase is done by Swedenergy, predicting an increase of 8.7 TWh resulting in an electricity demand of 81.7 TWh in 2045. The moderate increase in the scenarios is due to the increased electricity demand from new households and offices being held back by energy efficiency improvements in the sector.

The IVA scenario is forecasting an increase corresponding to 7 TWh due to population growth and new technology appliances. However, energy efficiency measures withhold the increase.

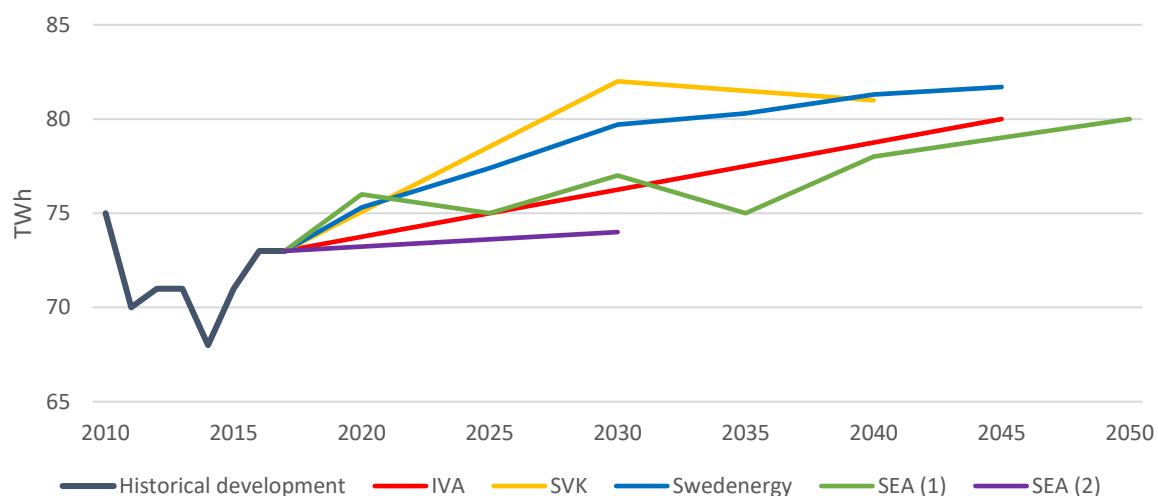


Figure 17: Comparison of the studied scenario's estimated national electricity demand in the residential and service sector.

The widespread in the forecasts is mainly due to different underlying assumptions in the scenarios. When applying the decision model to the chosen scenarios, **Figure 18**, it can be seen that three scenarios stand out with the most number of fulfilled parameters IVA, Swedenergy and SEA (1). SEA (1) does not meet the criteria for climate goals and therefore not chosen. IVA and Swedenergy have fulfilled the same number of parameters. However, IVA is the only scenario that fulfils the three main assumptions set in the thesis and are therefore chosen as the *Base scenario*. Appendix C gives a more detailed description of the studied scenarios different assumptions.

Scenario	Main assumptions			Energy efficiency measures	New industry	Population growth
	Climate goals	Competitiveness	Economic Growth			
IVA						
SVK						
Swedenergy						
SEA (1)						
SEA (2)						

Figure 18: Analysis of studied scenarios based on the decision model.

The *Base Scenario* is used as guidance for the *Regional Analysis*. The predicted increase in electricity demand in the industry is focused on the basic industry. The Chemical, Iron and steel and the Cement industries are predicted to stand for up to 88 % of the increase. The predicted increase in the transport sector includes road transports and rail traffic when predicting the electricity demand. **Figure 19**, illustrates the *Base Scenarios* prediction for each sector, and by that also illustrates what will be investigated in the *Regional Analysis*.

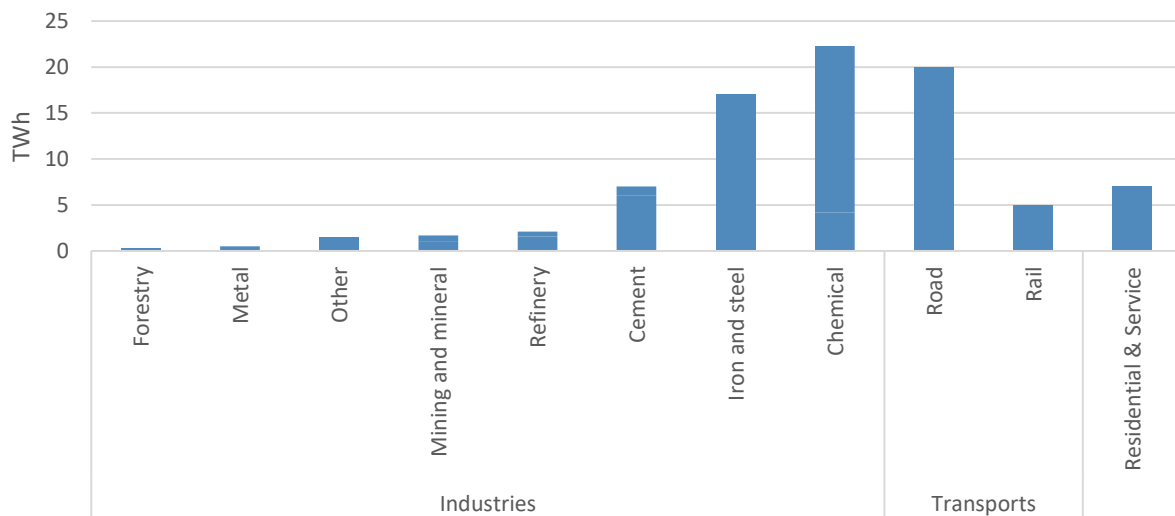


Figure 19: The base scenarios predicted a potential increase in each sector and subsector. Based on data from IVA (2019b, 2019c, 2019a).

6.2 Phase 2 - Regional analysis

The results for *Phase 2* consist of an assessment of in which regions the most significant changes in electricity demand will occur until 2045. An estimate of electrification potential is presented for four chosen regions.

6.2.1 Choice of regions

The allocation of CO₂-eq emissions included in the EU ETS during 2018 per region are shown in **Figure 20**. Two regions stand out with large shares of emissions. Västra Götaland has the largest share of GHG emissions from industries of 26 %. The large share is mainly because several major refinery and chemical industries are located in this region (Swedish Environmental Protection Agency, 2019b). The industries in Norrbotten has the second-largest share and stands for 20 % of the emissions. The majority of the emissions from industries in Norrbotten are emitted from the iron and steel industry and the mining industry.

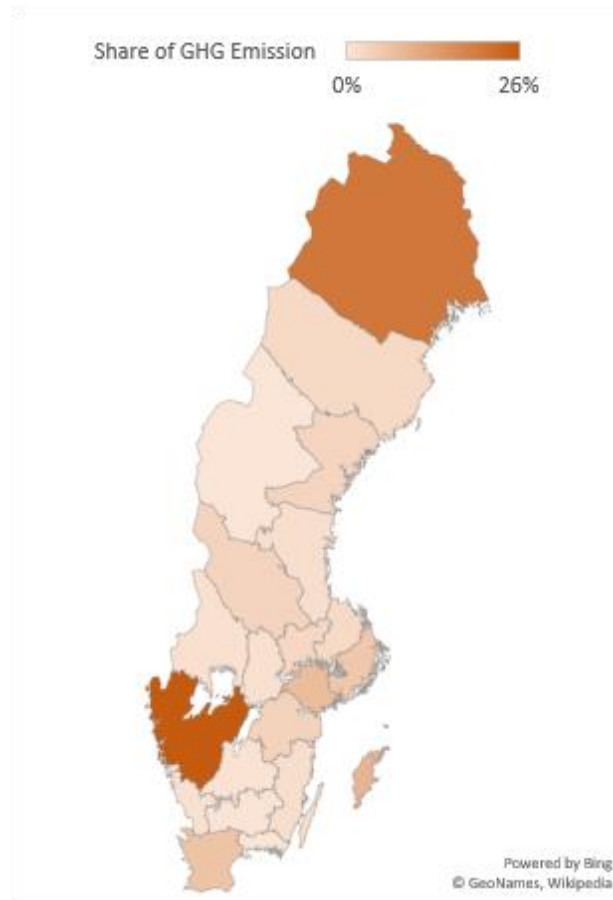


Figure 20: GHG emissions in 2018 from industries included in EU-ETS allocated per region.

Figure 21 illustrates where the most considerable regional population growth in relation to the current population is predicted. Large increases are predicted to be in city regions. The largest growth is forecasted in Stockholm, where the increase is predicted to be 31 % between 2020 to 2045. The increase is predicted to be 25 % in Region Skåne and 16 % in Region Västra Götaland between 2020 and 2045. Population in Region Norrbotten shows a predicted decrease of 5 % until 2045.

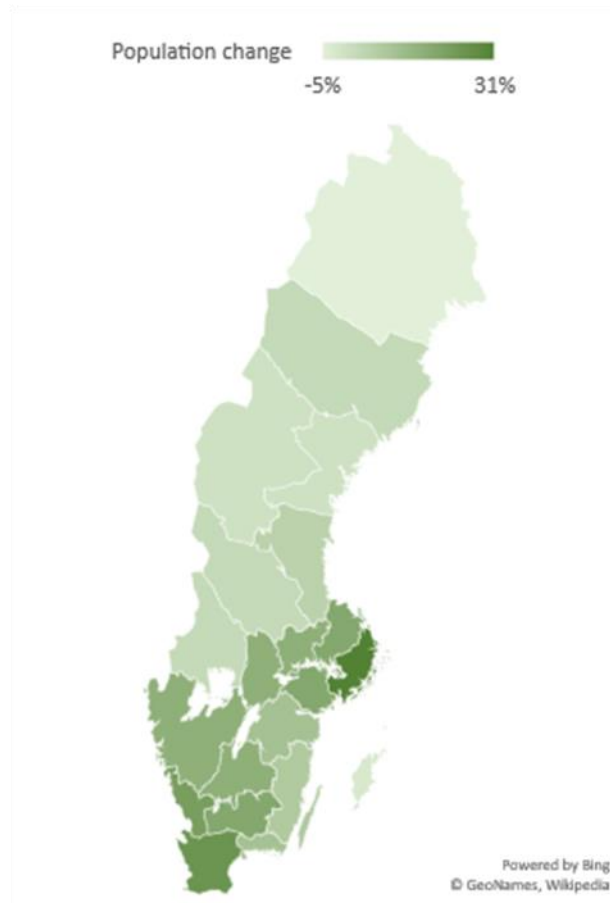


Figure 21: Predicted population change in the region between 2018 - 2045.

Figure 22 illustrates in what regions the volume of petroleum products for transportation is delivered. The total amount of fuel delivered amounted to 69.5 TWh. The regions with the highest shares of sold petroleum products aimed for transportation is located in large city-regions. Västra Götaland accounted for 18 %, Region Stockholm for 15 % and Region Skåne for 12 %.

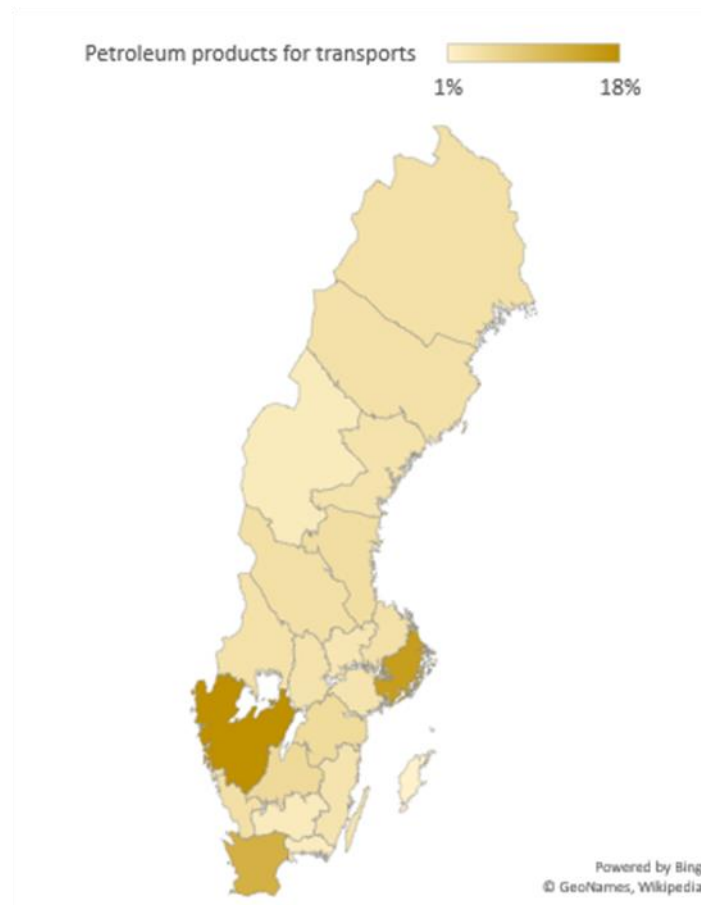


Figure 22: Regional distribution of the delivered volume of fossil fuels intended for transports during 2018. The share is put in relation to the total regional demand.

A weighted assessment based on the results presented in results in the choice of four regions for further studies:

- **Region Norrbotten** is chosen due to a large share of Sweden's GHG emissions from industries can be derived here.
- **Region Stockholm** is chosen due to high predicted population increase and a high share of delivered fossil fuels for transports.
- **Region Västra Götaland** is chosen due to the highest share of GHG emission from industries, high population growth and a high share of delivered fossil fuels for transports.
- **Region Skåne** is chosen due to high population growth and high share of delivered fossil fuels for transports.

6.2.2 Norrbotten

A summary of the identified electrification potential in the different sectors is shown in **Figure 23**. The electrification is predicted to be driven by decarbonisation of existing industries mainly. The total identified electrification potential is 10.7 TWh in annual demand, meaning that the total annual electricity demand within the region would increase from 7.1 TWh to 17.8 TWh.

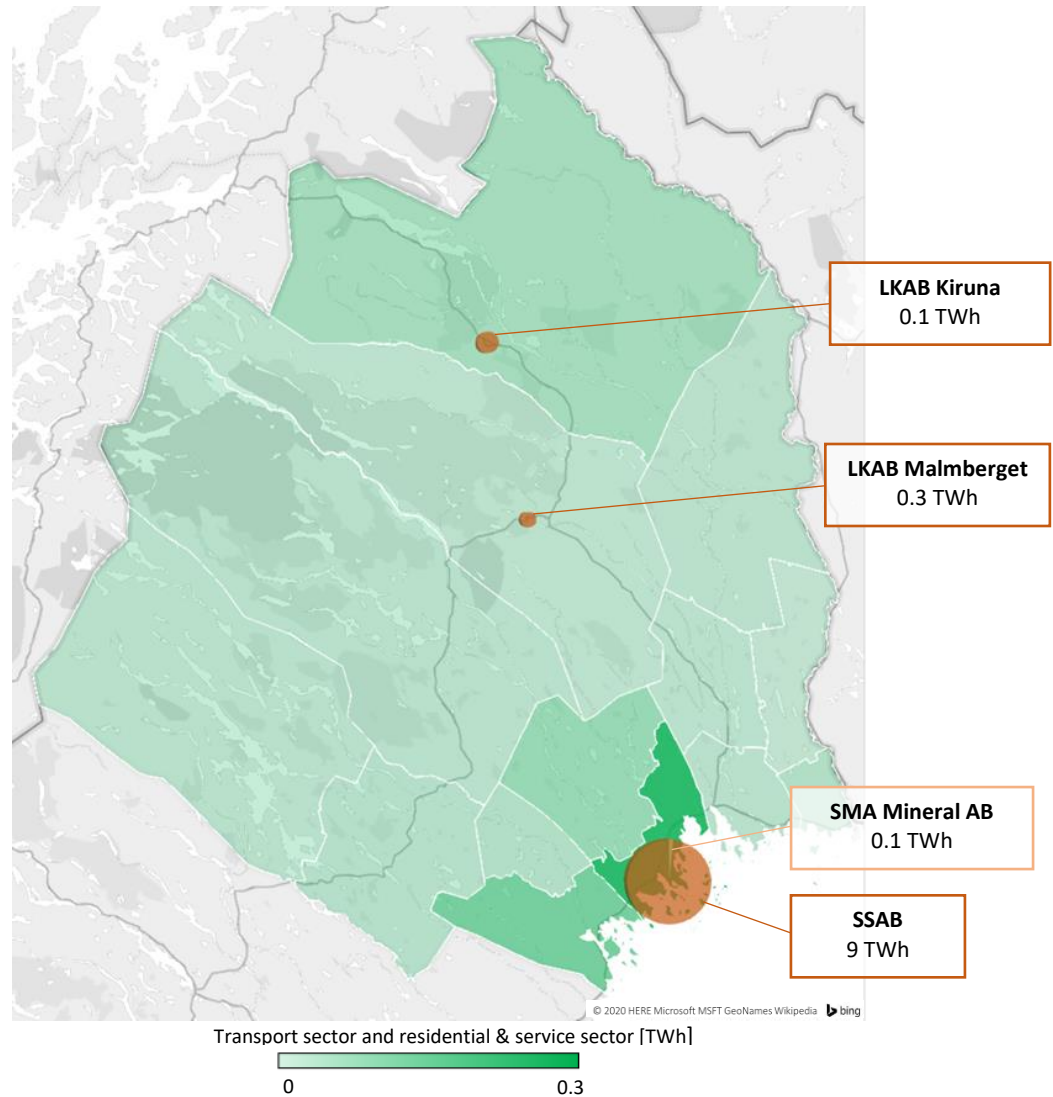


Figure 23: Identified electrification potential in Norrbotten for industries, road transports and residential and service sector.

6.2.2.1 Industry

The iron and steel industry stands for 78 % of the GHG emissions, and the mining industry stands for 16 % of the industrial emissions generated in the in Norrbotten. **Figure 24** shows the companies with the largest point source emissions. Five companies reported emissions larger than 40 Mtonne CO₂-eq during 2018 and are therefore investigated in the regional analysis. The industries that are not investigated stand for less than 1 % of the emissions and electricity and district heating stand for 3 %.

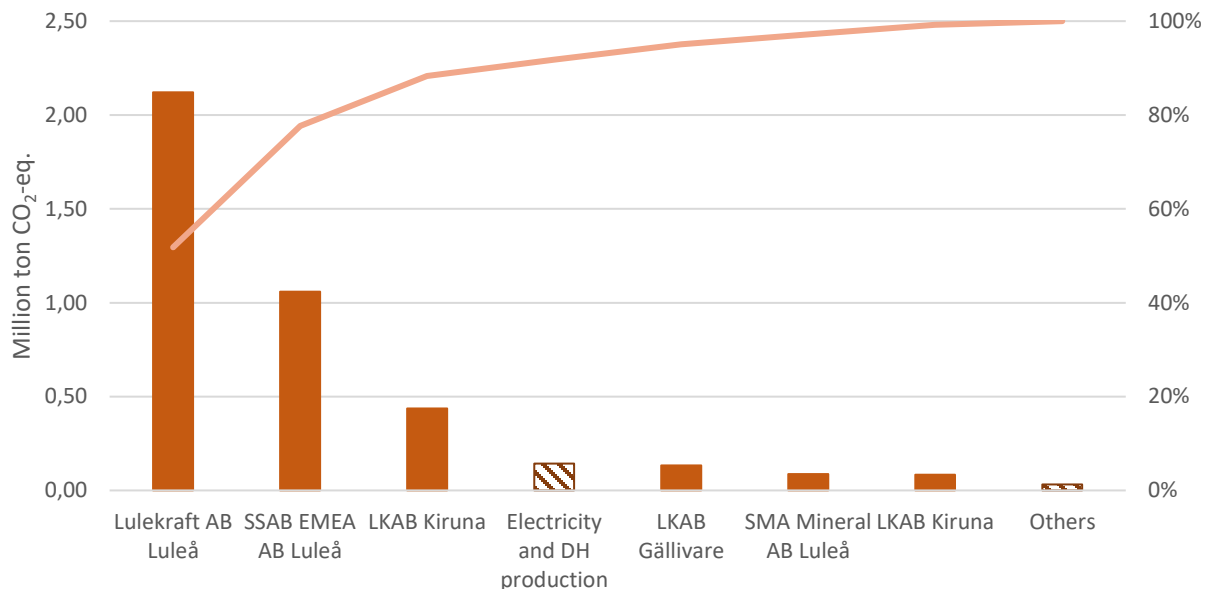


Figure 24: Distribution of emissions in Norrbotten included in the EU-ETS. Electricity and DH production is shown to illustrate the share of emissions coming from the investigated industries. Lulekraft AB is included as an industry because data is based on Naturvårdsverket's (2019b) categorization, where Lulekraft AB is included in the iron and steel industry. Based on data from Naturvårdsverket (2019b)

The investigation of the companies shows that a large-scale electrification in existing industry can take place in Norrbotten, mainly due to decarbonisation measures. The total identified electrification potential in the industry sector is 10.1 TWh, with an estimated power demand of around 1 100 MW. **Table 6** describes the underlying reasons for the estimated electrification potential in each industry. Appendix A2 provides a more detailed description of each industry.

Table 6: Potential electrification in the investigated industries in Norrbotten. A compilation of information given by interviews and through literature is presented together with assumptions conducted by the authors if needed to give an estimate of the future electricity demand.

Industry	Estimated electricity demand based on interviews and literature	Calculated estimations of electricity demand based on the authors' assumptions
Lulekraft AB	A possible decarbonisation route is believed to be that fossil excess gases will be replaced with excess heat from SSAB's hydrogen production. ^a	-
SSAB EMEA AB	<p>HYBRIT is expected to lead to an increased electricity demand of 3 488 kWh per tonne steel. The project is planned to proceed as follows:^b</p> <p>Demo phase: 2025-2035</p> <ul style="list-style-type: none"> - 250 000 – 500 000 tonne per year^c <p>Production phase 2035-</p> <ul style="list-style-type: none"> - 500 000 – 2 500 000 tonne per year^c 	<p>Implementation of the HYBRIT project could result in annual electricity demand of up to 9 TWh and 1 000 MW by 2035.</p> <p>Demo phase:</p> <ul style="list-style-type: none"> - 100 – 200 MW, 1 – 2 TWh/year <p>Production phase:</p> <ul style="list-style-type: none"> - 2035 200 – 1 000 MW, 2 – 9 TWh/year
LKAB	<p>80-90 % of emissions are generated in pelletizing plants. A conversion to bio-oil is currently considered as most likely. However, research is also ongoing on converting to plasma torches which would result in a significant increase in electricity demand.^d</p> <p>Electrification and automatization of mining operations will lead to an increased electricity demand.^d</p>	<p>Electrification through plasma torches in the pelletizing plants is estimated to lead to an increased annual electricity demand at the different sites of:</p> <ul style="list-style-type: none"> - Kiruna: 470 GWh and 60 MW. - Malmberget: 307 GWh and 38 MW. - Svappavaara: 96 GWh and 12 MW. <p>Electrification of internal transports is assumed to lead to an annual electricity demand at the different sites of:</p> <ul style="list-style-type: none"> - Kiruna: 8 GWh and 1 MW. - Malmberget: 10 GWh and 1 MW. - Svappavaara: 26 GWh and 3 MW.
SMA Mineral AB Luleå	<p>Emissions are generated in burners and chemical reactions. Three technologies are seen for decarbonisation:^f</p> <ul style="list-style-type: none"> - Electrification or the use of Hydrogen as fuel are possible solutions to decarbonise burners and is estimated to have approximately the same electricity demand. - CCS can be used as a supplemental measure to remove chemical reactions or as a single solution for all emissions. 	<p>Electrification or hydrogen produced through electrolysis is assumed to lead to an annual electricity demand of 107 GWh. Using CCS to reduce the remaining emissions from chemical reaction is assumed to lead to an additional 28 GWh per year. Implementation of these measures is estimated to lead to a power demand of 17 MW.</p> <p>If CCS is implemented as a single solution it is assumed that 33.8 GWh per year would be required.</p>

^aM. Nordlander (2020). ^bHYBRIT Development AB (2017). ^cSwedish Energy Agency et al. (2018). ^dFrohm (2020). ^eL. Nordlander (2020).

6.2.2.2 Transports

Electrification of road transports in Norrbotten gives an estimated annual electricity demand of 0.2 TWh in 2030 and 0.6 TWh in 2045. **Figure 25** shows the predicted electrification rate for the different road transports mode up until 2045. The increase is mainly due to the electrification of passenger cars and light trucks. A higher electrification rate than estimated could lead to a significant increase in electricity demand for heavy trucks relative to the other types of transports, see 100% electrification in **Figure 25**. Appendix D shows the input data used for calculating the estimated electrification.

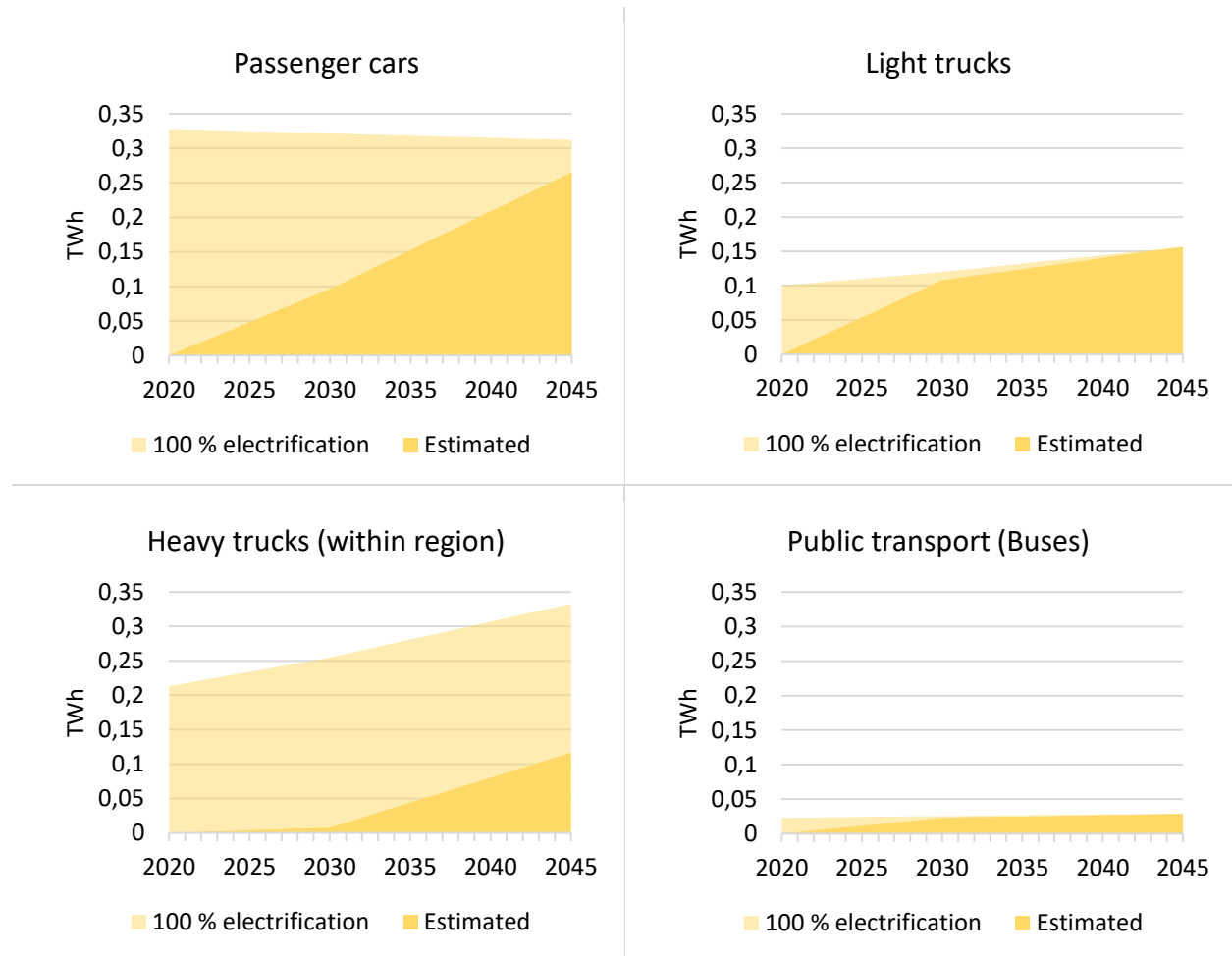


Figure 25: Estimated electricity demand due to the electrification of road transports in Norrbotten. The estimated demand is compared with the electricity predicted to be needed for 100 % electrification of the vehicle fleets.

The annual electricity demand from rail traffic is estimated to increase by around 0.1 TWh up until 2045.

6.2.2.3 Residential and service

The population in Norrbotten is predicted to decrease with 4.9 % until 2045. Electricity demand for the residential and service sector is therefore predicted to decrease by 0.1 GWh on the regional level.

A population increase is however predicted at local level in Luleå municipality and Piteå municipality. These movements imply that the electricity demand from the residential and service sector may concentrate to Luleå with 78 GWh and Piteå with 21 GWh due to urbanisation. Input data for estimating the electricity demand in the residential and service sectors are found in Appendix E.

6.2.3 Västra Götaland

A summary of the potential increased electricity demand from the different sectors is shown in **Figure 26**. The electrification in Västra Götaland is predicted to be driven by decarbonisation in the existing industry, but also by urbanisation and electrification of transports, primarily in Gothenburg municipality. The total identified electrification shows an increase of 21.2 TWh per year, meaning that the total annual electricity demand within the region would increase from 18.7 TWh to 39.9 TWh.

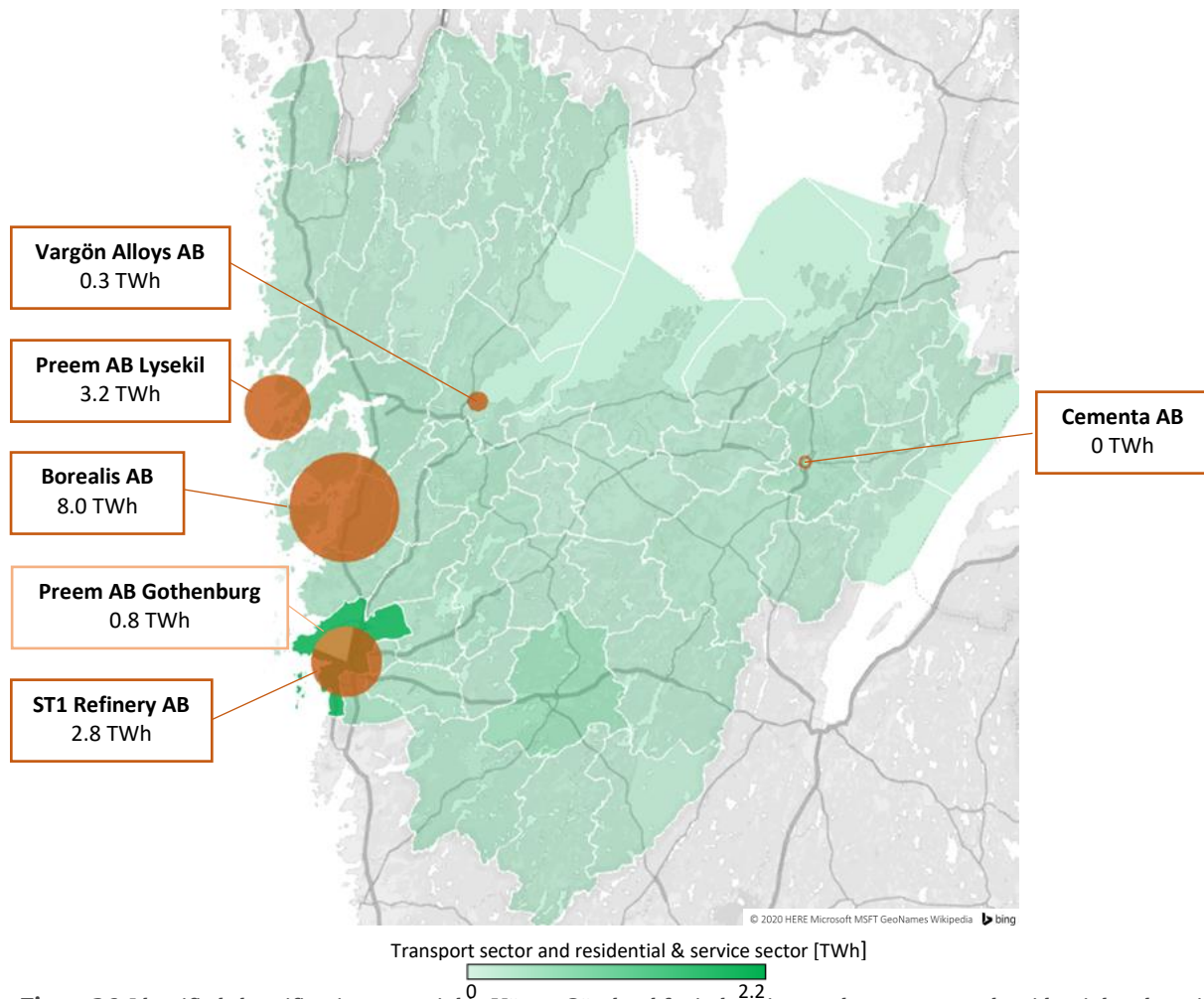


Figure 26: Identified electrification potential in Västra Götaland for industries, road transports and residential and service sector.

6.2.3.1 Industry

Industries in Västra Götaland accounts for 26 % of the GHG emissions included in the EU ETS in Sweden. Companies within the refinery industry and chemical industry stands out as large emitters in the region. **Figure 27** shows the companies with the largest point source emissions. These industries are investigated in the regional analysis. The industries that are not investigated stand for around 6 % of total emissions within the region and electricity and DH production stand for 12 %.

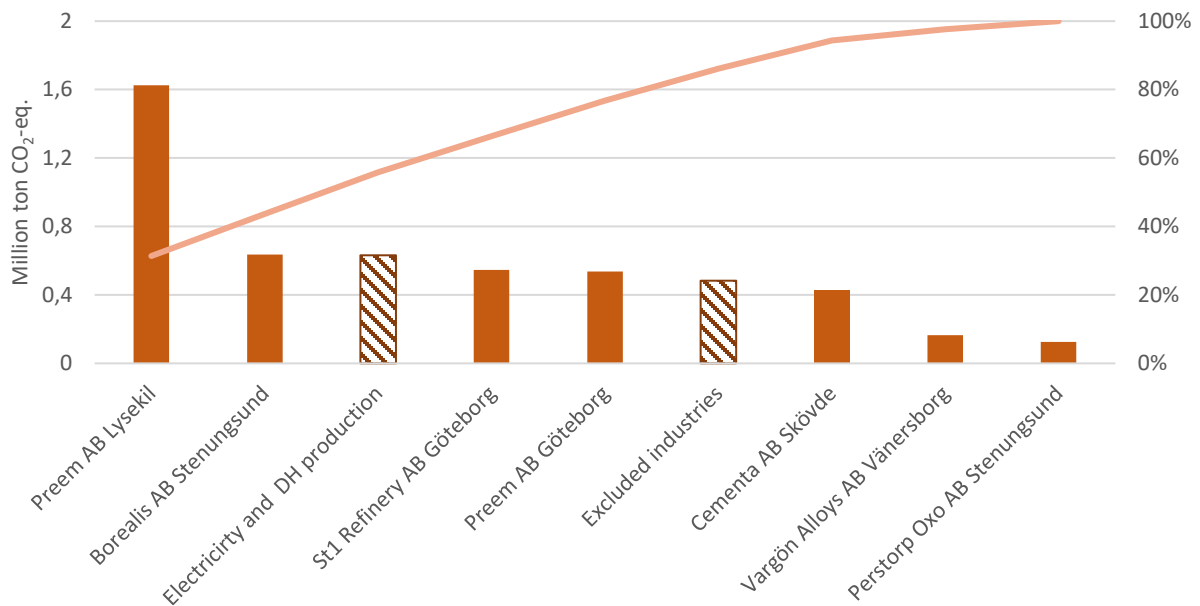


Figure 27: Distribution of emissions in Västra Götaland included in the EU-ETS. Electricity and DH production is shown to illustrate the share of emissions coming from the investigated industries. Based on data from Naturvårdsverket (2019b).

The identified electrification potential in the investigated industries is 15.9 TWh and 2 000 MW. The most significant potential is shown along the coast, between Gothenburg and Stenungsund. However, it should be noted that some of the identified potentials are theoretical maximum values, and that full realisation of all potentials should, therefore, be seen as quite unlikely. **Table 7** describes the underlying reasons for the estimated electrification potential in each industry. Appendix A3 provides a more detailed description of each industry.

Table 7: Potential electrification in the investigated industries in Västra Götaland. A compilation of information given by interviews and through literature is presented together with assumptions conducted by the authors if needed to give an estimate of the future electricity demand.

Industry	Compilation of data collection	Estimated electricity demand based on assumptions
Preem AB	<p>It is estimated that Preem will need to invest in two hydrogen plants, one in Gothenburg with a power demand of 100 MW and one in Lysekil with a power demand of 400 MW by 2035 in order to reach the climate targets set.^a</p> <p>A feasibility study is ongoing for establishing hydrogen production with a power demand of around 20 MW at the refinery in Gothenburg by 2024.^a</p>	<p>When assuming continuous operation for the hydrogen production, the annual electricity demand is estimated to be:</p> <ul style="list-style-type: none"> - 0.8 TWh in Gothenburg - 3.2 TWh in Lysekil
Borealis AB	<p>The alternatives seen for decarbonisation are:</p> <ul style="list-style-type: none"> - Direct electrification or fuel conversion to hydrogen produced via electrolysis which is estimated to require up to 500-600 MW for full decarbonisation. - Implementation of CCU which is estimated to require around 525 MW.^b <p>An alternative to decarbonisation of today's processes is to change the feedstock into using plastic waste. This solution is investigated as a part of the project "Plastic Cracking", and a realization could lead to an increased demand of 1 000 MW.^b</p>	<p>When assuming continuous operation for the different alternatives, the annual electricity demand is estimated to be:</p> <ul style="list-style-type: none"> - 4.0-4.8 TWh for the electrification route. - 4.2 TWh for the CCU route. - 8.0 TWh for the plastic cracking route.
ST1	<p>A full-scale transformation into bio- and electro fuel production could increase the electricity demand by 300-350 MW, which should be seen as a theoretical high upper limit.^{a,c}</p>	<p>When assuming continuous operation, the annual electricity demand is estimated to be up to 2.8 TWh.</p>
Cementa AB	<p>Different routes for decarbonisation is researched, but it is difficult to say what route will be taken for the production site in Skövde.^d</p> <p>However, the focus for the production site in Skövde is to substitute coal with bio-based fuels as well as substitute limestone with recycled material.^d</p>	-
Vargön Alloys	<p>Two routes are seen for decarbonisation:^e</p> <ul style="list-style-type: none"> - Conversion to bio-coal instead of fossil coal - Implementation of CCS. <p>There is also the possibility for a higher utilization of the current production capacity. Full utilization could lead to an additional 30 MW being required.^e</p>	<p>If implemented, CCS is assumed to result in an electricity demand of 50 GWh per year and 6.5 MW.</p> <p>Higher utilization of production capacity with the assumption of continues operation would lead to 240 GWh</p>
Perstorp OXO AB	<p>Currently no plans for large scale electrification. Sees a gradual transition to biomass as more likely.^a</p>	-

^aJannasch et al. (2020).^bPettersson (2020).^cKarlsson (2020).^d(Cementa AB, 2020).^eJansson (2020).

6.2.3.2 Transports

Electrification of road transports in Västra Götaland gives an estimated annual electricity demand of 1.3 TWh in 2030 and 3.3 TWh in 2045, see **Figure 28**. The increase is mainly due to the electrification of passenger cars. Appendix D shows the input data used for calculating the estimated electrification.

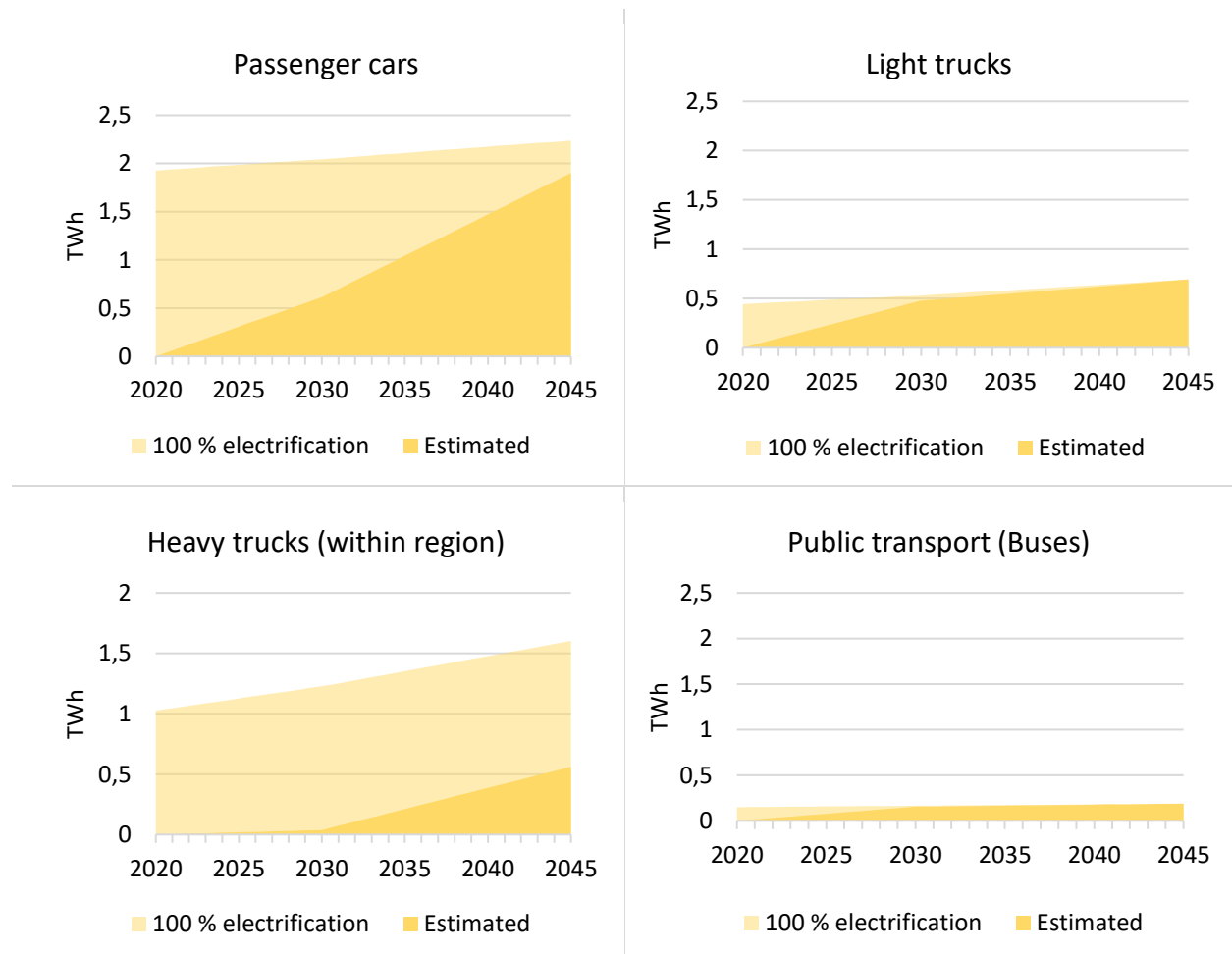


Figure 28: Estimated electricity demand due to the electrification of road transports in Västra Götaland. The estimated demand is compared with the electricity predicted to be needed for 100 % electrification of the vehicle fleets.

The annual electricity demand from rail traffic is estimated to increase by around 0.8 TWh up until 2045.

6.2.3.3 Residential and service

The population in Västra Götaland is predicted to increase with 16.5 % until 2045. The annual electricity demand for the residential and service sector is therefore predicted to increase by approximately 2.0 TWh on regional level.

At the local level, the municipality of Gothenburg stands out as the municipality where the largest increase in population is predicted. If the electricity demand is assumed to be proportional to population change, the annual electricity demand from the residential and service sector would increase by 0.9 TWh in the municipality of Gothenburg. The second and third largest increase at local level would be seen in the municipality of Borås and the municipality of Mölndal, both with an estimated increase of 0.1 TWh per year. Input data for estimating the electricity demand in the residential and service sectors are found in Appendix E.

6.2.4 Stockholm

An overview of the estimated electrification potential in the different sectors is shown in **Figure 29**. The electricity demand in Stockholm is predicted to be driven by urbanisation and electrification of transports. The total identified electrification shows an increase of 9.5 TWh in annual demand, meaning that the total annual electricity demand within the region would increase from 20.5 TWh to 30.7 TWh.

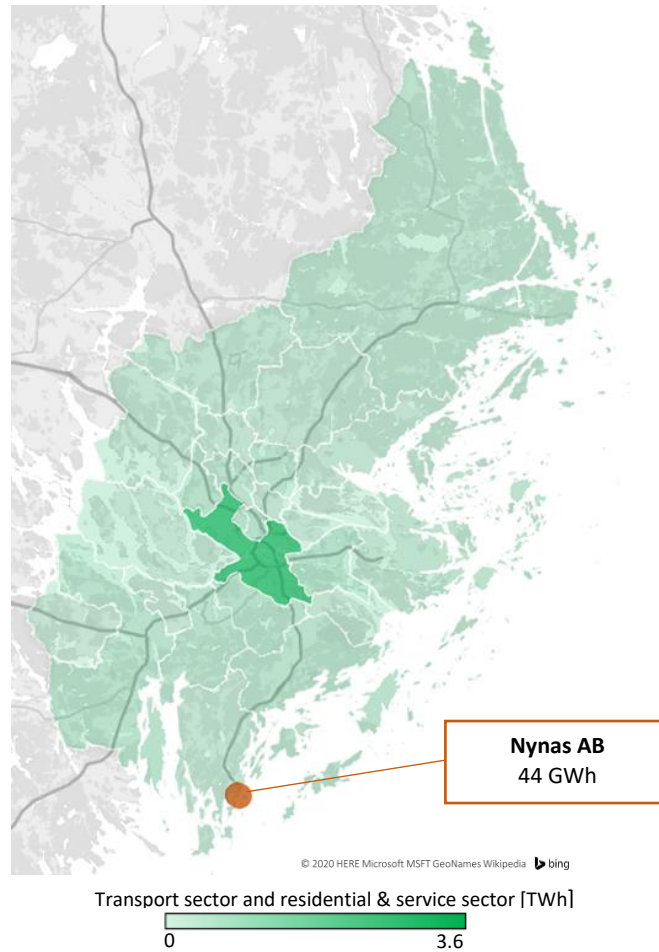


Figure 29: Identified electrification potential in Stockholm for industries, road transports and residential and service sector.

6.2.4.1 Industry

Industries in Region Stockholm accounts for 6 % of the GHG emissions included in the EU ETS in Sweden. The majority of the emissions comes from local electricity and district heating production. The refinery Nynas AB, standing for 13 % of the regional emissions included in EU-ETS, is the only industry that is investigated. **Figure 30** shows how the point source emissions in the region are distributed among the different actors (Swedish Environmental Protection Agency, 2019b). It should be noted that the majority of the emissions comes from electricity and DH production, which is assumed to convert to biomass. The industries that are excluded together stands for less than 1 % of the regional emissions.

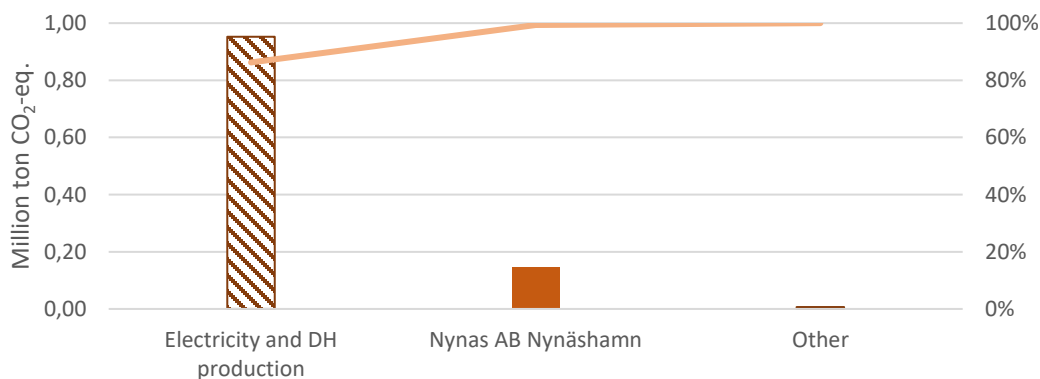


Figure 30: Distribution of emissions in Stockholm included in the EU-ETS. Electricity and DH production is shown to illustrate the share of emissions coming from the investigated industries. Based on data from Naturvårdsverket (2019b).

The identified electrification potential in the existing industry can be seen as modest as only one industry is investigated. **Table 8** describes the underlying reasons for the estimated electrification potential. More details about Nynas can be found in Appendix A4.

Table 8: Potential electrification in the investigated industries in the region of Stockholm. A compilation of information given by interviews and through literature is presented together with assumptions conducted by the authors if needed to give an estimate of the future electricity demand

Industry	Estimated electricity demand based on interviews and literature	Calculated estimations of electricity demand based on the authors' assumptions
Nynas AB	No official information obtained about how Nynas AB is planning to decarbonize and whether it may lead to an increased electricity demand.	If CCS dimensioned for the current emission volume, the electricity demand is assumed to be 44 GWh per year and 5 MW if used in continuous operation.

6.2.4.2 Transports

Electrification of road transports in Region Stockholm gives an estimated annual electricity demand of 1.8 TWh in 2030 and 4.5 TWh in 2045, see **Figure 31**. The increase is mainly due to the electrification of passenger cars. A significant increase is also estimated for light trucks up until 2030, corresponding to an annual electricity demand of 0.8 TWh. Appendix D shows the input data used for calculating the estimated electrification.

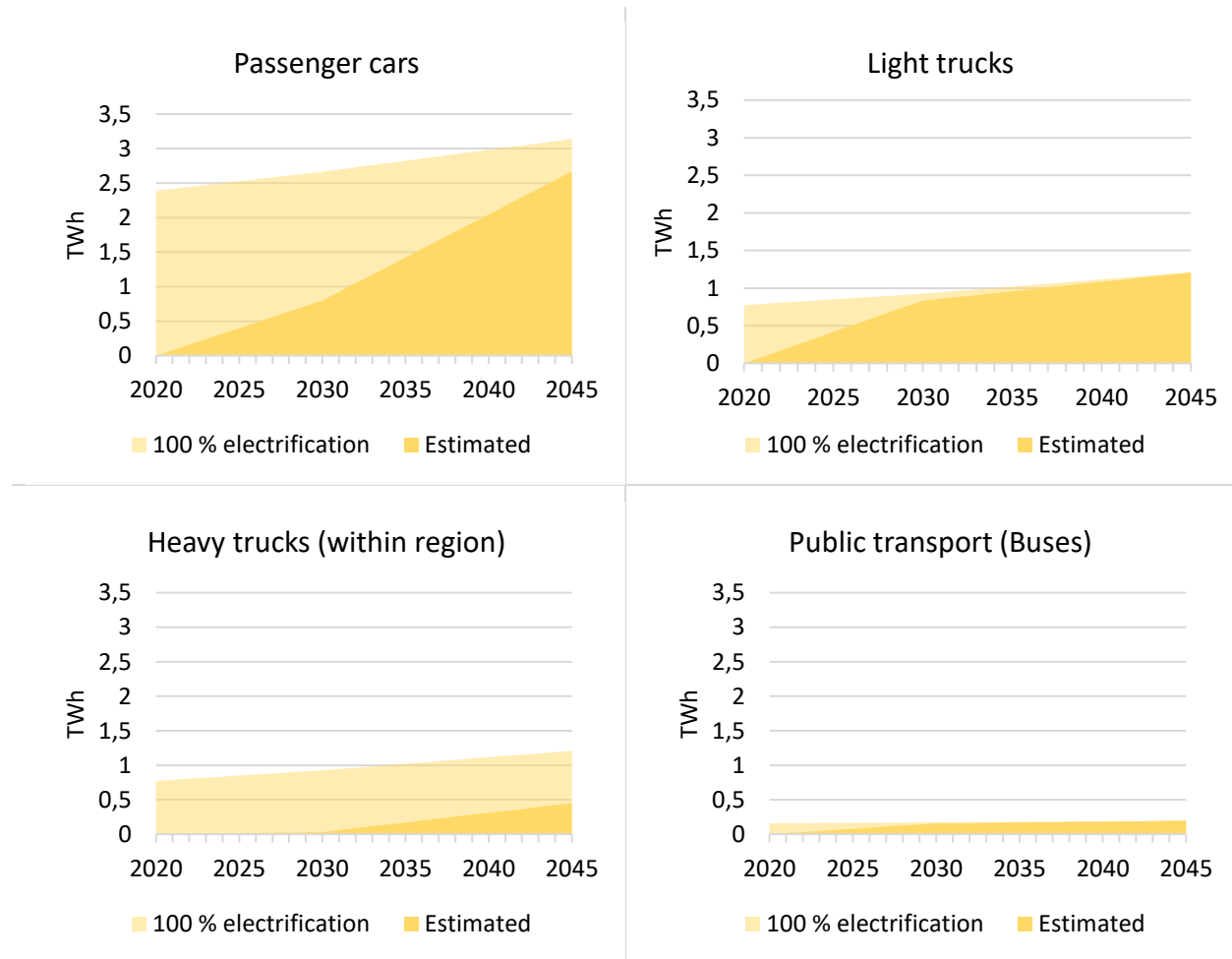


Figure 31: Estimated electricity demand due to the electrification of road transports in Stockholm. The estimated demand is compared with the electricity predicted to be needed for 100 % electrification of the vehicle fleets.

The annual electricity demand from rail traffic is estimated to increase by around 1.2 TWh up until 2045.

6.2.4.3 Residential and service

The population in Region Stockholm is predicted to increase with 30 % until 2045. The electricity demand for the residential and service sector is therefore predicted to increase by approximately 5.0 TWh on regional level.

At the local level, the municipality of Stockholm stands out as the municipality where the largest increase in population is predicted. If the electricity demand is assumed to be proportional to population change, the annual electricity demand from the residential and service sector would increase by 1.8 TWh in the municipality of Stockholm. The second and third largest increase at the local level would be seen in the municipality of Nacka and the municipality of Huddinge, both with an estimated increase of just over 0.2 TWh of increased annual electricity demand until 2045. Input data for estimating the electricity demand in the residential and service sectors are found in Appendix E.

6.2.5 Skåne

An overview of the estimated electrification potential in the different sectors is shown in **Figure 32**. The electricity demand in Skåne is predicted to be driven by urbanisation and electrification of transports. The total identified electrification potential is estimated to 6.3 TWh in annual demand, meaning that the total annual electricity demand within the region would increase from 13.0 TWh to 19.3 TWh.

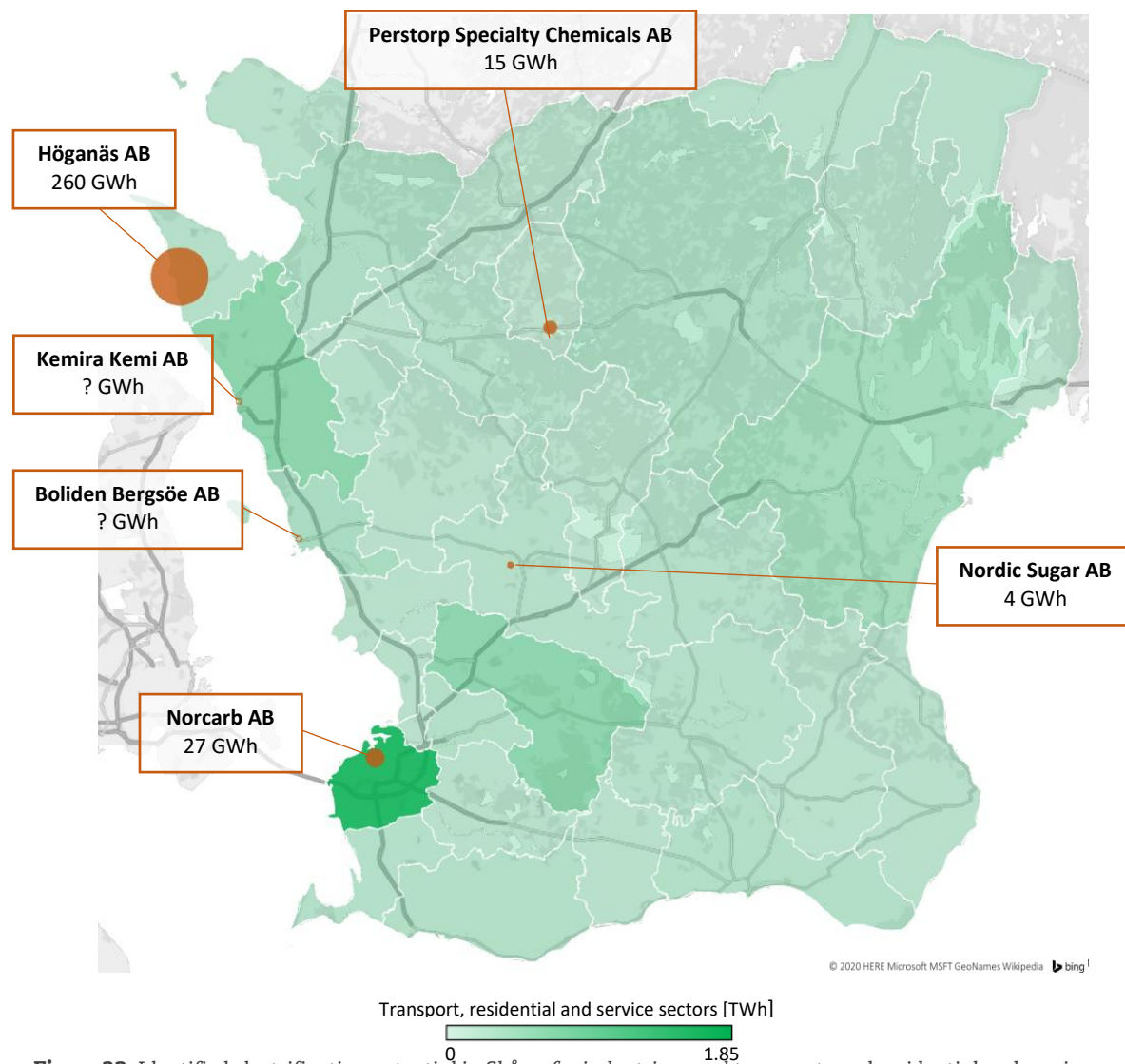


Figure 32: Identified electrification potential in Skåne for industries, road transports and residential and service sector.

6.2.5.1 Industry

Industries in Skåne accounts for 6 % of the GHG emissions included in the EU ETS in Sweden. The largest share of emissions comes from electricity and district heating production. The companies that are excluded from the regional analysis, together constitute a relatively large proportion of emissions in the industrial sector in the region. The companies included operate in a mix of industries, e.g., the iron and steel industry, the refinery industry, the food industry and the chemical industry. **Figure 33** shows the companies with the largest point source emissions (Swedish Environmental Protection Agency, 2019b). These companies are investigated in the regional analysis.

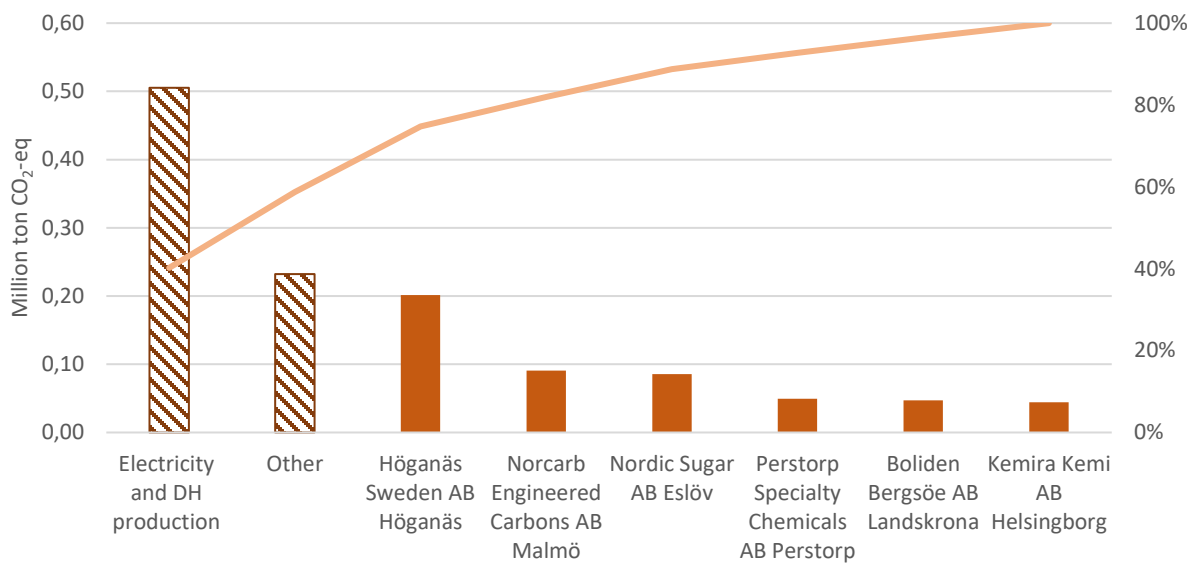


Figure 33: Distribution of emissions in Stockholm included in the EU-ETS. Electricity and DH production is shown to illustrate the share of emissions coming from the investigated industries. Based on data from Naturvårdsverket (2019b).

The investigation of the companies shows an uncertain electrification potential, where none of the industries investigated have any concrete plans for large scale electrification. The results indicate that the industries will primarily work towards a conversion to biomass. **Table 9** describes the underlying reasons for the estimated electrification potential in each industry.

Appendix A5 provides a more detailed description of each industry.

Table 9: Potential electrification in the investigated industries in Skåne. A compilation of information given by interviews and through literature is presented together with assumptions conducted by the authors if needed to give an estimate of the future electricity demand.

Industry	Estimated electricity demand based on interviews and literature	Calculated estimations of electricity demand based on the authors' assumptions
Höganäs Sweden AB	<p>Primarily looking into techniques based on biomass for decarbonisation. The identified possibilities for electrification are:^a</p> <ul style="list-style-type: none"> - Electrification of current hydrogen production is estimated to require 60 GWh per year and 7-10 MW. - A conversion of fossil fuel use through electrification is estimated at 150-200 GWh per year 10-20 MW. 	-
Norcarb Engineered Carbons AB	Production is based on a fossil-based feedstock, and no opportunities for a conversion of the feedstock can be seen. ^b	If CCS is assumed to be implemented, it is estimated to result in an electricity demand of 27 GWh per year and 3 MW .
Nordic Sugar AB	<p>A conversion to biogas is seen as most likely for decarbonisation.^c</p> <p>A relocation of a refinery, moving from Arlöv to Örtofta, will increase the electrical power demand at the site by approximately 1.5 MW by 2022.^c</p>	Based on the specified operating time, the electricity demand for the relocated refinery is estimated to be 4 GWh per year.
Perstorp Specialty Chemicals AB	No official information obtained about how Perstorp Specialty Chemicals AB is planning to decarbonize and whether it may lead to an increased electricity demand.	If CCS is assumed to be implemented, it is estimated to result in an electricity demand of 15 GWh per year and 2 GW .
Boliden Bergsöe AB	<p>Emissions comes from natural gas, coke and plastics. The alternatives seen for decarbonisation are conversion to biogas, bio coal and electrification.^d</p> <p>It is estimated to be possible with an electrification corresponding to the use of 25 GWh natural gas per year.^d</p>	Due to uncertainties in the process design, no estimate has been made in how much electricity would be required if 20 GWh of natural gas were electrified.
Kemira Kemi AB	Emissions comes from the use of natural gas. Several options for decarbonisation are investigated. Today it is not possible to predict how the electricity demand can change ^e	-

^aM. Pettersson (2020).^bNorcarb Engineered Carbons AB (2020).^cDahlgren (2020).^dArnerlöf (2020).^eGunnarsson (2020).

6.2.5.2 Transports

Electrification of road transports in Skåne gives an estimated annual electricity demand of 1.1 TWh in 2030 and 3.1 TWh in 2045. The increase is mainly due to the electrification of passenger cars. **Figure 34** shows the predicted electrification rate for the different road transports mode up until 2045. Appendix D shows the input data used for calculating the estimated electrification.

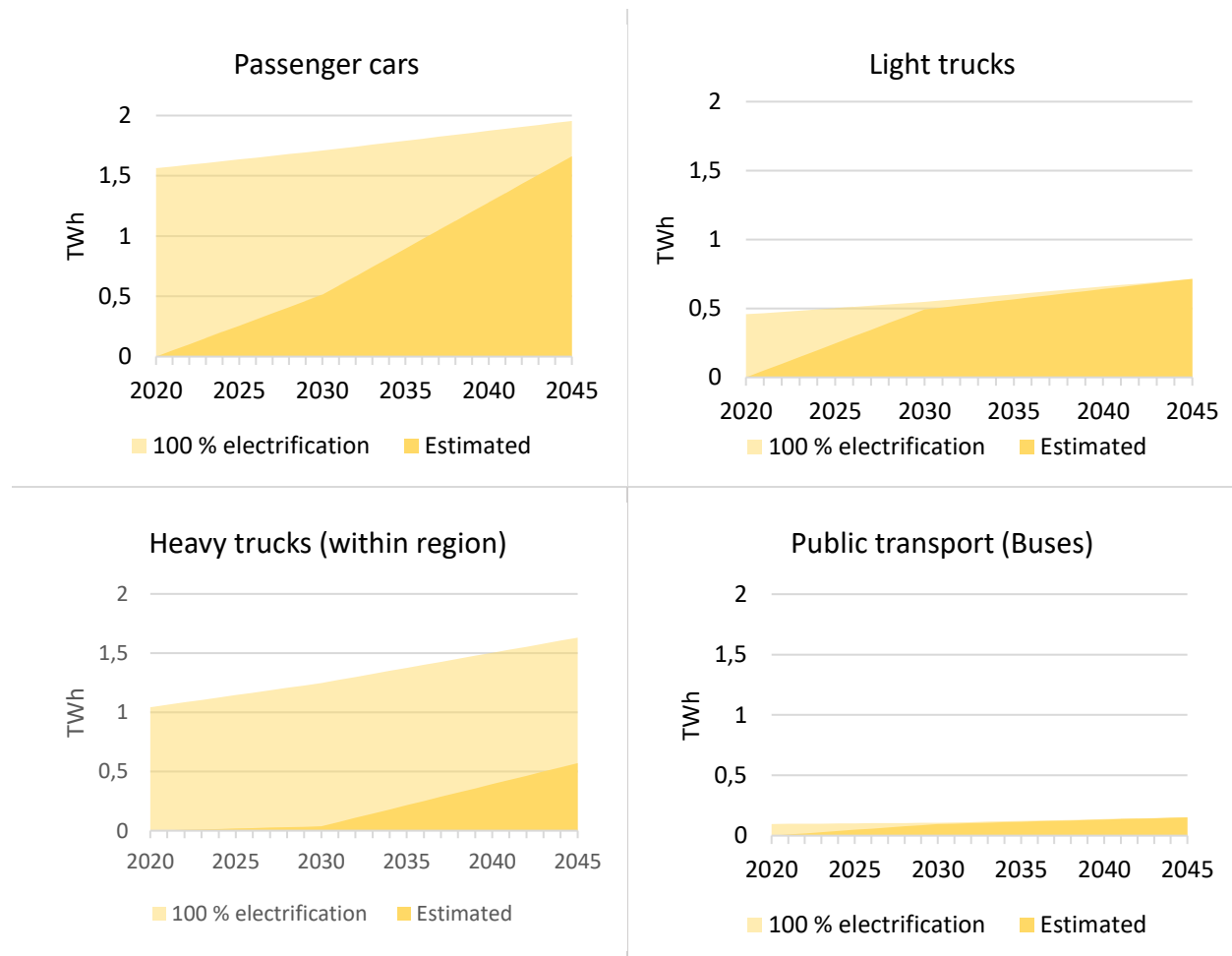


Figure 34: Estimated electricity demand due to the electrification of road transports in Skåne. The estimated demand is compared with the electricity predicted to be needed for 100 % electrification of the vehicle fleets.

The annual electricity demand from rail traffic is estimated to increase by around 0.7 TWh up until 2045.

6.2.5.3 Residential and service

The population in region Skåne is predicted to increase with 24 % until 2045. The electricity demand for the residential and service sector is therefore predicted to increase by approximately 2.2 TWh on regional level.

At the local level, the municipality of Malmö stands out as the municipality where the largest increase in population is predicted. If the electricity demand is assumed to be proportional to population change, the annual electricity demand from the residential and service sector would increase by 1.0 TWh in the municipality of Skåne. The second and third largest increase at the local level would be seen in the municipality of Lund and the municipality of Helsingborg, both with an estimated increase of just over 0.2 TWh of increased annual electricity demand until 2045. Input data for estimating the electricity demand in the residential and service sectors are found in Appendix E.

6.2.6 Regional compilation

The total identified electrification potential for the four investigated regions is 26.3 TWh in the industry sector, 14.3 in the transport sector and 9.0 TWh in the residential and service sector.

Figure 35 illustrates the identified electrification potential at the regional level.

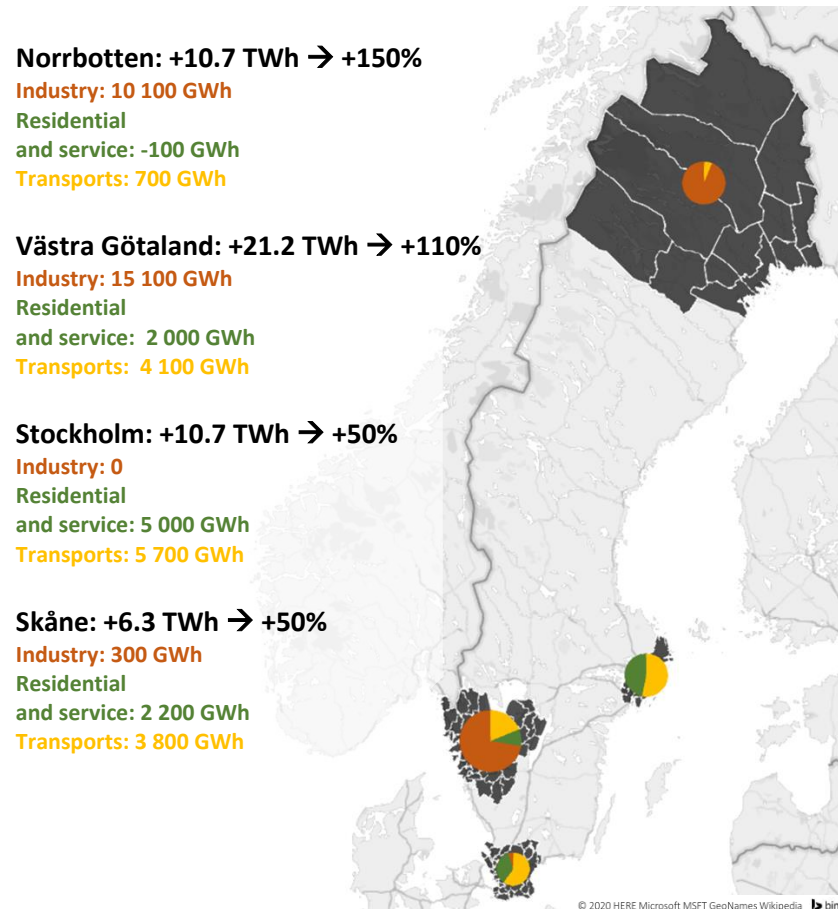


Figure 35: Identified electrification potential by 2045 for each sector and investigated region. The circles show the identified potential in each sector, where the size of the circle is proportional to the identified demand.

A comparison shows that IVA's estimate for residential & service at the national level, is lower than the identified electrification potential within the residential and service sector in the investigated regions. IVA predicts an increase with 7 TWh for the whole country, which is 3.4 TWh lower than the calculated result in the four regions.

Some municipalities stand out at the local level, in which the identified electrification potential would lead to a more than doubled electricity demand compared to today's level. The largest percentage increase is found in Luleå municipality within Norrbotten, where the demand can increase with a factor of nine. In Västra Götaland, almost a fivefold increase can be seen in Lysekil municipality and Stenungsund municipality. These three increases are all mainly driven by electrification in the industrial sector. In Stockholm, Sundbyberg municipality stand out as area where the electricity demand is estimated to be doubled, even though no electrification potential

is identified in industries. Instead, it is the electrification of the transport sector as well as strong population growth that is the major drivers for the increase in demand. **Figure 36** illustrates the percentage increase of electricity demand at a municipal level in the investigated regions. However, the largest percentage increase does not necessarily indicate the largest increase in TWh. E.g., the percentage increase in Stockholm municipality is 50 % and corresponds to around 3 600 GWh while the increase in Sundbyberg municipality corresponds to around 420 GWh.

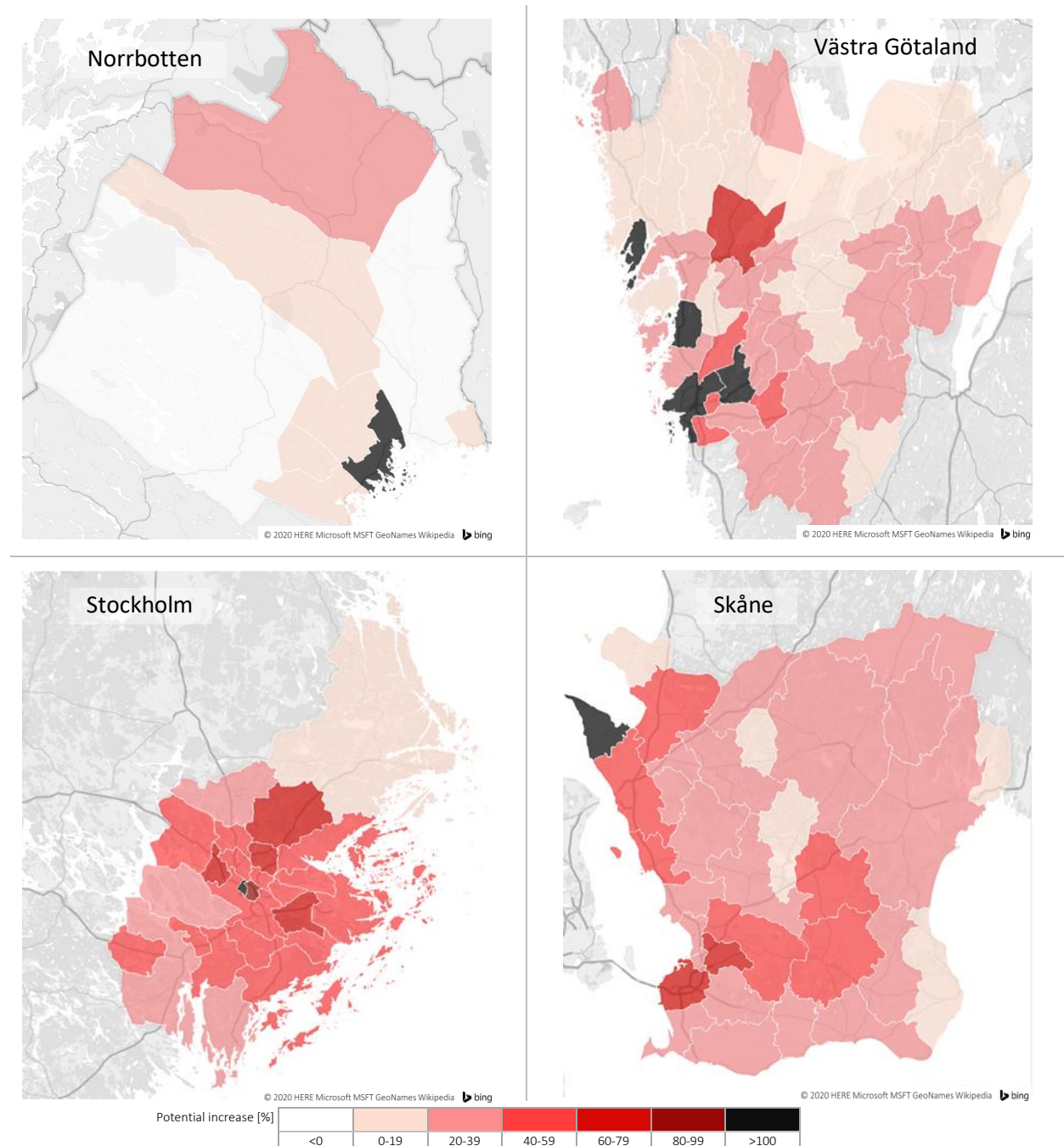


Figure 36: The percentage increase in annual electricity demand at the municipal level if the identified electrification potential were to be realised.

6.3 Phase 3 - Grid analysis

The main findings from interviews with grid operators are presented, divided by the main question. More detailed interview summaries can be found in Appendix B2.

Is there capacity shortage in the region today?

Most operators stated that the situation at present is quite ok, but that it is starting to get strained in specific local areas. Of the regions investigated, the most strained situation is described as being in Region Stockholm. **Table 10** shows the main findings for the question, divided per region.

Table 10: Main findings from interview responses on current electricity grid situation

Region	Main findings	Grid operator
General	Capacity shortages are seen in the areas around Stockholm and Malmö, but not in the areas around Luleå and Gothenburg	Svk ^a
Norrbotten	The situation is generally good, and capacity is still available in the grid and the region benefits from having large scale electricity production	Vattenfall AB ^b
Västra Götaland	The situation is generally good, but it starts to get strained in specific areas.	Vattenfall ^c
	No acute problems are currently seen in the local grid in Gothenburg.	Göteborg Energi ^d
Stockholm	The situation in Vattenfall's regional grid is generally quite good, but it starts to get strained in specific areas.	Vattenfall ^e
	The transmission grid has reached its max capacity and need to be reinforced.	Vattenfall ^e
Skåne	Continuously worked with increasing the grid capacity in their grid in the Helsingborg area. Currently no problems with capacity restraints in the local grid.	Öresundskraft ^f
	The situation is strained in southern parts of Skåne, but the acute capacity shortages are temporarily solved.	E.ON ^g

^aEdfast (2020). ^bVattenfall Eldistribution AB Two representatives (2020). ^c(Vattenfall Eldistribution AB, 2020c).

^dAndersson (2020). ^eVattenfall Eldistribution AB Stockholm (2020). ^fÖresundskraft AB (2020). ^gTheelin (2020).

Is there a risk that capacity shortage will occur in the future?

The majority of the grid operators describes that an electrification that gives rise to a large increase in electricity demand will cause capacity shortages in the electricity grid if no measures are taken. The best situation is described in Norrbotten, where a significant increase in power outtake is described as possible. **Table 11** shows the main findings for the question, divided per region.

Table 11: Main findings from interview responses on the possibility of meeting an increased electricity demand

Region	Main findings	Grid operator
General	<i>Risk for capacity restraints in all regions if no measures are taken</i>	Svk ^a
	<i>Grid situation is momentarily and can change quickly. An application for a large power outage might change the situation from good to restraint</i>	Svk ^a Göteborg Energi ^b
Norrbotten	<i>There is a risk for a strained situation in the transmission grid along the coast in Norrbotten due to the establishment of energy-intensive industries.</i>	Vattenfall ^c
	<i>Problems are not seen with increasing the electricity demand with 2000 – 3000 MW within the in Norrbotten.</i>	Vattenfall ^c
	<i>Establishment with large power outage, too far north might be a problem since there is no transmission grid there.</i>	Vattenfall ^c
Västra Götaland	<i>Realisation of all potential electrification of industries would require the grid capacity to be doubled. However, realisation of the full potential is seen as unlikely.</i>	Vattenfall ^d
	<i>A gradual electrification of industries is believed to occur, which will increase the possibility to manage the increased demand.</i>	Vattenfall ^d
	<i>The conditions for meeting an increased electrification in the Gothenburg area is seen as relatively good. The local grid is currently not dimensioned for the potential electrification in the area, but it is believed to be possible to meet the future demand with good forecasts.</i>	Göteborg Energi ^b
Stockholm	<i>Several ongoing projects for reinforcements and expansions in the grid which should make the situation with capacity shortages resolved by 2025</i>	Vattenfall ^e
Skåne	<i>The opportunities to meet increased electricity demand is generally good. However, it is mentioned that if an industry would apply for a big power demand, each case must be evaluated individually. It is also mentioned that Öresundskraft, as a local grid operator, is dependent on the development of the regional and national grids.</i>	Öresundskraft ^f
	<i>Because Svk gives priority to reinforcements in the transmission grid, the aim is to enable electrification within E.ON's grid.</i>	E.ON ^g
	<i>The time when it was possible to sign a new contract for large connections immediately is now past.</i>	E.ON ^g

^aEdfast (2020). ^bAndersson (2020). ^cVattenfall Eldistribution AB Two representatives (2020). ^dVattenfall Eldistribution AB Norrbotten (2020). ^eVattenfall Eldistribution AB Stockholm (2020). ^fÖresundskraft AB (2020). ^gTheelin (2020).

What are the underlying reasons to why capacity shortages are occurring in the electricity grid?

The reason mentioned by most respondents was that the lead time for the application for a concession is too long. It was also described that the lead time for concession has diverged from the lead time for establishing a new type of industries, which results in that the electricity grid cannot be expanded at the same rate as the electricity demand increases. **Table 12** shows the main findings for the question.

Table 12: Main findings from interview responses on why capacity shortages are occurring.

Main findings	Grid operator
<i>The concession process is too long, primarily for line concession in regional and national grid.</i>	All
<i>Applications for a new connection to the grid have become larger in both number and magnitude.</i>	Svk ^a Vattenfall ^b Vattenfall ^c
<i>The demand is increasing faster than the rate at which the grid can be reinforced.</i>	Svk ^a Vattenfall ^d
<i>Lead times for concession have become longer and diverged from lead times for the establishment of new industries.</i>	Vattenfall ^d Vattenfall ^b
<i>It is difficult to act proactively when expanding the grid since the grid operators need to be able to justify the expansion.</i>	Vattenfall ^d Vattenfall ^b
<i>Companies apply for new connection in several locations to “scan the area”, and not for actual establishment.</i>	Vattenfall ^d
<i>Shut down of local electricity production.</i>	Vattenfall ^c E.ON ^e
<i>Expansion of cities – urbanisation.</i>	Vattenfall ^c
<i>Lack of available capacity in the transmission grid</i>	E.ON ^e

^a(Brunge, 2020).^b (Vattenfall Eldistribution AB, 2020c).^c(Vattenfall Eldistribution AB, 2020a).^d(Vattenfall Eldistribution AB, 2020b).^e(Thelin, 2020).

What can grid operators do to prevent capacity shortages?

When discussing how grid operators can work to prevent capacity shortages, three main areas were mentioned: communication, flexibility measures, and grid infrastructure measures.

Communication and collaboration between grid operators and other stakeholders were mentioned as factors contributing to a successful grid development. Facilitating for customers by informing about appropriate areas for the establishment was also a factor mentioned. **Table 13** shows the main findings for the question associated with the communication.

Table 13: Main findings from interview responses on communication measures to prevent capacity shortages

	Main findings	Grid operator
Communication	<i>Communication between all stakeholders is seen as a critical factor in the grid development.</i>	Svk ^a Vattenfall ^b E.ON ^c
	<i>Currently good communication with regional grid operators, but the communication with large industries could be improved.</i>	Svk ^d
	<i>Extended collaboration between different grid operators when forecasting electricity demand.</i>	Svk ^a Göteborg Energi ^e
	<i>Better defined project portfolios that show what capacity is available in the long and short term and what measures are needed to implement them in order to speed up the decision making process.</i>	Göteborg Energi ^e
	<i>Communication with municipalities could be improved</i>	Vattenfall ^b
	<i>Offer companies the possibility of discussing suitable locations early in an establishment processes.</i>	Vattenfall ^f Öresundskraft ^g
	<i>Tries to give customers an approximate lead time early in an establishment process.</i>	Vattenfall ^h
	<i>Participate in networking meetings to help influence the development of the electricity market.</i>	Öresundskraft ^g
	<i>Participate in regional and national scenario work.</i>	Öresundskraft ^g

^a(Brunge, 2020). ^b (Vattenfall Eldistribution AB, 2020c). ^c(**Thelin, 2020**). ^d(Edfast, 2020). ^e(Andersson, 2020). ^f(Vattenfall Eldistribution AB, 2020b). ^g(Öresundskraft AB, 2020). ^h(Vattenfall Eldistribution AB, 2020a).

Reinforcements and expansion of electricity grids is mentioned as a vital part of preventing capacity shortage. Having local grid reserve powerplants was also lifted as a factor by the local grid operators. **Table 14** shows the main findings for the question associated with grid measures.

Table 14: Main findings from interview responses on grid reinforcement measures to prevent capacity shortages

	Main findings	Grid operator
Grid measures	<i>Reinvestments and reinforcements in the current grid.</i>	Svk ^{a,b}
	<i>Be more proactive in the grid planning process, e.g., by preparing grid concessions proactively.</i>	Vattenfall ^c
	<i>Aim at expanding the grid in pace with incoming applications and increased demand.</i>	Vattenfall ^d
	<i>Aim at maintaining local grid reserve powerplants.</i>	Göteborg Energi ^e Öresundskraft ^f E.ON ^g
	<i>Work with projects that have long time horizons.</i>	Svk ^a
	<i>Grid planning based on good forecasting.</i>	Göteborg Energi ^e

^a(Brunge, 2020).^b(Edfast, 2020).^c(Vattenfall Eldistribution AB, 2020b).^d(Vattenfall Eldistribution AB, 2020a).^e(Andersson, 2020).^f(Öresundskraft AB, 2020).^g(Thelin, 2020).

All respondents mentioned flexibility measures as a tool to reduce the risk of capacity shortages. Several of the responses were about using flexibility to meet the expected electrification in the transport sector. **Table 15** shows the main findings for the question associated with flexibility.

Table 15: Main findings from interview responses on flexibility measures to prevent capacity shortages

	Main findings	Grid operator
Flexibility	<i>Flexible resources to balance demand and supply, and relief the grid, e.g., hydrogen, are needed.</i>	Svk ^{a,b}
	<i>Flexibility solutions to meet electrification in the transport sector are seen as important.</i>	Vattenfall ^c Göteborg Energi ^d
	<i>Prevent large-scale use of fast chargers during times of high load.</i>	Göteborg Energi ^d
	<i>Large scale electrification in the industry sector will have to be managed by flexibility if the concession process is not made more efficient.</i>	Vattenfall ^c
	<i>Believes that it is difficult to find a business model for flexibility in regions with available capacity and surplus production.</i>	Vattenfall ^e
	<i>Flexibility solutions is seen as interesting until the grid is expanded and dimensioned for the new demand.</i>	Vattenfall ^f
	<i>Encourage flexible use of electricity as a way of optimizing the load on the grid.</i>	Öresundskraft ^g
	<i>Try to control electricity demands to arise outside of daily peaks</i>	Vattenfall ^c Vattenfall ^f Göteborg Energi ^d
	<i>Participates in a project called "Switch" which is a digital marketplace for flexibility to avoid capacity shortages by optimizing the use of the grid.</i>	E.ON ^h

^a(Brunge, 2020).^b(Edfast, 2020).^c(Vattenfall Eldistribution AB, 2020c).^d(Andersson, 2020).^e(Vattenfall Eldistribution AB, 2020b).^f(Vattenfall Eldistribution AB, 2020a).^g(Öresundskraft AB, 2020).^h(Thelin, 2020).

What can be done to facilitate grid operators' efforts to prevent capacity shortages?

When discussing what can be done to facilitate grid operators' efforts to prevent capacity shortages, two main areas were mentioned, improve the concession application process and communication from customers.

Several respondents mention a more efficient application process for a concession to shorten lead times as desirable. It is also mentioned that grid infrastructure should be given higher priority in community planning. **Table 16** shows the main findings for the answers associated with the concession.

Table 16: Main findings from interview responses regarding concession in order to facilitate for grid operators.

	Main findings	Grid operator
Concession	<i>A better structured and more agile concession application process for shorter lead times are needed.</i>	Svk ^a E.ON ^b
	<i>Greater national interest for grid infrastructure</i>	Svk ^a Vattenfall ^c
	<i>A quicker and more efficient concession process, but important to keep the process democratic</i>	Vattenfall ^c
	<i>A quicker and more efficient concession process to reduce the risk of having to speculate</i>	Vattenfall ^d

^a(Brunge, 2020).^b(Thelin, 2020).^c(Vattenfall Eldistribution AB, 2020c).^d(Vattenfall Eldistribution AB, 2020b).

A common answer was also that an early dialogue is desirable at, e.g., the establishment of a new industry or the development of a city. **Table 17** shows the main findings for the answers associated with the communication.

Table 17: Main findings from interview responses regarding concession, in order to facilitate for grid operators

	Main findings	Grid operator
Communication	<i>Industries that are interested in new establishments should establish early contact with the grid operator.</i>	Svk ^a Vattenfall ^b E.ON ^c
	<i>Compiled and structured information about local development in the region would be beneficial in the grid planning process.</i>	Vattenfall ^d E.ON ^c
	<i>The municipality involves the grid operators when preparing new local plans.</i>	Öresundskraft ^e E.ON ^c

^a(Edfast, 2020).^b(Vattenfall Eldistribution AB, 2020b).^c(Thelin, 2020).^d(Vattenfall Eldistribution AB, 2020c).^e(Öresundskraft AB, 2020).

7. Discussion

The results have given a good basis for analysis and discussion. A considerable electrification potential has been identified, which risks creating major challenges linked to the electricity grid capacity. Uncertainties cannot be avoided as the future is attempted to be predicted, which makes transparency in assumptions and analysis methodology important.

7.1 Evaluation of research methodologies

The research methodologies used to answer the research problem have contributed to a comprehensive result for the three different phases and has highlighted the thesis' problem statement. The use of different data collection methodologies resulted in different types of findings, but could also be used for validation and triangulation.

7.1.1 Literature study

The literature study aims at describing the current conditions and future challenges in the Swedish electric power system. Structured literature searches were conducted for finding scientific literature, but it has been noted that there is not a particularly wide range of previous research done from a Swedish perspective. There is a large number of search terms and combination of search terms relevant for the researched area, and other combinations of these than those tested could have yielded more relevant search results. However, citation searches contributed to a more comprehensive overview of previous research. Literature that has been used but is not written with perspectives based on Swedish conditions is primarily about subjects where the perspective has no significant impact, or it is clearly stated that it is not necessarily applicable to Swedish prerequisites.

There is a wide range of literature produced by state-owned enterprises, grid operators and industry organizations describing the grid situation from a Swedish perspective. In several cases, several articles and texts have provided the same picture of what the grid situation looks like or what the challenges are and thus have been able to support each other and increase credibility. Several findings from the literature study were also confirmed during the interviews with industry and grid operator representatives which results in a triangulation.

7.1.2 Interviews

The use of semi-structured interviews to collect data about the conversion of industries and to get the perspective from the grid operators have been necessary since several of most of the studied industries do not have published material about their electrification potential. The interviews with both industry and grid operator representatives resulted in information that confirmed findings from the literature study, but also new information that the literature study did not cover.

A strength is that both authors attended all interviews and therefore, could take notes and to pick up different perspectives for the summary. Not recording the interviews is in retrospect considered as the right decision. The lack of opportunity to re-listen the interviews several times is considered to be offset by the fact that all respondents were allowed to give feedback on the summaries. This led to clarifications being made in several summaries. However, a drawback with using interviews to collect data is that it is time-consuming and limitations had to be made on the number of investigated regions and interviewed companies. One factor that may have been limiting is that it could not be ensured that the interviews were conducted with the most appropriate representative to answer the interview questions. The choice of respondent has relied upon the interviewed company to select a suitable representative based on a summary of the thesis purpose and aim.

7.2 Discussion of results

The long-term scenarios studied in the national analysis shows a spread in estimated electricity demand with predictions between 171-207 TWh in 2045, which, would be an increase of 40-60 % compared to 2017. However, long-term scenarios have many uncertainties and only describes what would happen if the assumptions set in the scenarios were to happen, which means that the scenarios studied in both the *National Analysis* and the results from the *Regional Analysis* should be seen as one of several possible developments.

Looking at national scenarios alone means missing out on local changes. The result indicates that large increases may occur locally, mainly as a result of electrification in industry and cities as a result of urbanisation. Electrification in the transport sector is believed to result in an increased electricity demand in basically all populated areas.

7.2.1 Electrification of industry will require foresight

The methodology used for identifying electrification potential within industries shows that a small proportion of emissions from the industrial sites in Norrbotten and Stockholm are excluded. This indicates that the electrification potential as a result of decarbonisation, should not be that large in the excluded industries in these regions. Due to a large number of industries with relatively small emissions in Västra Götaland and Skåne, the proportions of emissions

excluded in these two regions are greater. This indicates that there could be a significant additional electrification potential that has not been identified. However, based on the results from *Phase 2*, it can be seen that industries with smaller GHG emissions, in general, see a lower increase in electricity demand in the future than industries with large emissions.

The results also show that relatively large shares of the GHG emissions within the regions comes from electricity and district heating production. If the development does not align with the assumption that power and heat production converts to biomass, a transition to heat production with heat pumps or implementation of CCS for current process emissions could be alternative developments. Such development would mean that there is further electrification potential here as well. There is also the possibility of bio-CCS, where, e.g., Stockholm Exergi, as one of the first companies in the world, is investigating the possibility of implementing bio-CCS. However, as Levihn *et al.* (2019) stated, implementation is not profitable today, despite the possibility of achieving negative emissions.

Another factor that is not covered by the identified electrification potential is the development in already electrified industries or industries that use other non-fossil-based energy carriers. Establishment of new industries may also result in an increased demand for electricity. E.g., the company Node Pole has identified sites suitable for new industry establishment in three of the four investigated regions. The sizes of the identified sites are relatively large, where the accumulated sum of power capacity amounts to 1 045 MW for seven sites in Norrbotten, 585 MW for five sites in Västra Götaland and 20 MW for five sites in Stockholm (Node Pole, no date). As was described by several of the interviewed grid operators, the conditions for new connections to the grid can change quickly if the electricity demand for existing or new customers increases. Therefore, the possibility of utilizing the full power capacity at all sites is considered uncertain. E.g., Vattenfall Eldistribution AB Norrbotten (2020) states that all the power capacity that Node Pole presents for the sites in Norrbotten cannot be realized and utilized at once.

The majority of the investigated industries have set targets for decreasing the CO₂-eq emissions but do not have concrete plans on how to decarbonise their processes. The lack of plans risks becoming an obstacle in reaching the climate targets if an electrification route is chosen. Large-scale electrification that requires the transmission grid to be reinforced needs to be communicated well in advance, which is confirmed by the majority of the interviewed grid operators. With today's permit processes, a process for expanding the transmission grid would need to start shortly after 2030 to be ready by 2045. Rissman *et al.* (2020) predicts that large-scale implementation of hydrogen production through electrolysis and CCS will take place beyond 2035, which are technologies that are discussed in several of the industries in Sweden with the largest GHG emissions. However, an implementation beyond 2035 would put considerable pressure on the grid operator's on meeting the electricity demand such implementation would result in. It will, therefore, be important for the industries to communicate what routes are considered in order to facilitate for the grid operators. Electrification that only requires reinforcements in the regional and local grids probably provide a slightly larger timespan within

which the industry needs to decide which path to choose if decarbonisation is to take place before 2045.

Sandberg *et al.* (2019) describes that different routes for decarbonisation most likely will need to be taken for different industries not to risk a non-secure energy supply or too high energy prices. Several of the large industries have stated that they are currently investing in different types of pilot projects, often to explore several different routes for decarbonisation of their processes, either via conversion to biomass, direct electrification, zero-carbon hydrogen or CCS. These solutions are in line with the development that Rissman *et al.* (2020) describes as essential for decarbonising the industry sector.

Even greater uncertainties about the development are seen in the smaller industrial companies that do not have the same long-term strategic work. Instead, it is perceived that smaller industries follow the development of different technologies and are ready when an appropriate technology is commercialized, rather than being involved in the development themselves. Several of the investigated industries confirms what is written by Nilsson *et al.* (2017), that the technologies for decarbonisation is currently too expensive, and as companies active on global markets, an increased price for their products cannot be afforded. A price that makes the technology profitable could lead to several industries wanting to implement the technology at once, thus putting pressure on secure access to electricity. However, this development would contradict the development that is described in the literature by Nilsson *et al.* (2017) and in interviews with several of the grid operators, where changes in the industry sector is believed to occur over time.

As mentioned by Foster (1986), Nilsson *et al.* (2017) and Rissman *et al.* (2020), there is a need for R&D to commercialize technologies that can be used as decarbonisation measures in the industry sector, and the development would be facilitated by well-developed countries taking the lead. Several of the investigated industries shows willingness to be a driving force in the development, where ongoing projects in the R&D phase have been identified, e.g. Hybrit, CemZero, electrification and automatization within the mining industry and fossil-free feedstocks in the refinery industries. Hydrogen production through electrolysis and carbon capture technologies is also examples of emerging technologies that many of the investigated large industries shows interest in. However, some companies are waiting on the market to commercialize products that they can implement. This indicates that the technology development following an s-curve pattern described by Foster (1986) may be applicable, and that successful implementation of new technology within the large base industry may give rise to a second wave of large-scale implementation.

7.2.2 Electrification in the transport sector is expected to lead to a significant increase in electricity demand

The electricity demand within the transport sector is strongly dependent on the electrification rate of the different modes of transports, as well as how passenger- and freight transport flows develop. Heavy transport has been assumed to have a slow electrification rate compared to other modes of road transport. Battery operated heavy trucks is something that is being discussed more and more frequently, and could lead to a faster electrification rate, and thus also a significantly greater electricity demand. However, if the development will be in line with the national freight transport strategy (Ministry of Enterprise and Innovation, 2018), road freight will to a certain extent be replaced by rail and sea freight, which could decrease the electrification potential for road freight transports.

Shipping has been excluded in the assessment of the electrification potential in the investigated regions. However, as the Swedish Energy Agency (2017) stated, the electricity demand in ports may increase significantly as a result of increased shore-supply. This could become an unforeseen development, especially in the Gothenburg, Skåne and Norrbotten regions, in which Sweden's six largest ports are located (Transport Analysis, 2016).

It is predicted that the electrification of passenger cars will be the major factor for an increased electricity demand within the transport sector. The compilation of the interviews with the grid operators shows a general picture that the operators do not see any problems with meeting the new demand from charging electric vehicles if the charging is conducted in a smart way using flexibility solutions to steer the electricity demand to not occur at daily power peaks. However, it was mentioned that home charging might become a problem since the grid operator do not know where the chargers will be installed. If flexibility measures fail, electrification of the transport sector could lead to significant increases in daily power peaks. The interpretation of the grid operators is that they do not see such great risk regarding this, and rely on flexibility measures when assessing the future grid situation.

Several modes of road transport are excluded, e.g., military transports, motorcycles and mopeds, these are however considered negligible when compared to other road transports. Busses and heavy transports that occurs to or from other regions than the investigated are also not covered in the regional investigation. However, the electrification potential that is missed due to these delimitations is assumed to be relatively small since most heavy transports and bus trips are conducted within the investigated region. Another factor that can have an impact is that the electricity demand is higher per kilometre in cold weather, which would lead to an increase in electricity demand during the winters.

7.2.3 Great uncertainties in how the electricity demand will change in the residential and service sectors

The comparison of national scenarios shows that all studied scenarios predict that the electricity demand in the residential and service sector will increase until 2045, albeit relatively slowly. Because the regional analysis is based on the *Base scenario* and that all investigated regions except Norrbotten are predicted to have strong population growth, electricity demand is also expected to increase at the regional level. However, the interviews with the grid operators showed that there are great uncertainties about how the development will evolve. Several grid operators described that they saw a possibility of a decreased electricity demand as a result of efficiency improvements, even though there is simultaneous population growth. Such a decrease would mean that the electricity demand per capita within the residential and service sectors that has been relatively constant during the last thirty years would decrease. However, Wiesner *et al.*'s (2019) belief, that cities will not be able to continue to grow without resulting in increased electricity demand, is more in line with the thesis' results and thus further show that opinions differ.

Energy efficiency measures are also included in the *Base Scenario*, but since it could not be determined how this affected the estimated electricity demand, energy efficiency improvements were not implemented in the regional analysis. This difference in assumptions could explain why the regional estimate is quite high, with a total identified electrification of 9 TWh in the four regions, compared with the *Base Scenario*'s predicted increase of 7 TWh on a national level. The predicted population growth is also seen as a possible explanation of the difference, where the *Regional Analysis* is based on a slightly stronger population growth than the *Base Scenario*.

A weakness with the methodology for estimating the electrification potential within the residential and service sectors is that it does not take the regional and local conditions into considerations, except population changes. Ma *et al.* (2017) uses the building characterizations, the district layout, local microclimate, social and economic standard as impact factors when modelling the district load for distributed energy systems. Ma *et al.* (2017) also concludes that making a model for load forecasting of distributed energy systems with satisfactory accuracy needs high quantization of impact factors and comes with a large computing workload. Statistical methods with a low quantization are concise but imprecise. The Swedish Energy Agency (2019) also states that the statistical data for making a valid forecast for domestic electricity and business electricity are lacking for this purpose.

One of the critical factors that will determine how the electricity demand in the sector will change is which techniques that will be used for heating. If district heating continues to be dominant, the likelihood that the electricity demand in the sector will increase is probably significantly lower than if heat pumps become dominant. Regardless of how current electricity demand in residents are changing, a new type of demand is likely to arise as a result of the electrification of passenger

cars being charged at home. Home charging risk putting pressure on the local grids to be able to manage the new type of electricity demand.

7.2.4 Challenging to increase the grid capacity at sufficient speed

Findings from the interviews with the grid operators indicates that there is a wish for an extended collaboration and exchange of information between grid operators and other stakeholders, in order to be able to make better forecasts. Nilsson *et al.* (2017) describes that a system perspective is needed in order to maintain a stable energy system where energy comes at competitive prices. Improved communication between grid operators and stakeholders could contribute to a better system perspective among different stakeholders.

The overall perception given by the grid operators was that there are relatively good opportunities to meet the potential electrification in the studied regions, as long as the grid operators are informed of the demands that may arise in sufficient time. Electrification of the transport sector will mainly be a driver for investments in the local grids, and establishment of larger customers like data centres might affect investments at both regional and national grid levels (Stattnett *et al.*, 2019).

It is challenging to work proactively with grid planning due to today's permit processes linked to the expansion of electricity grids, since the expansions need to be motivated socioeconomically or that there is a confirmed electricity demand. While new demands arise with shorter lead times, the permit process is described to have become more complicated and time-consuming, especially the application for a line concession. As several of the interviewed grid operators have confirmed, it can take over ten years to develop a new power grid. These lead times mean that there is a need to have a good understanding of what reinforcements will be required as early as 2030 to ensure that the electricity grid capacity will be expanded until 2045. Another option is to speed up the permit process to allow shorter lead times for power grid expansions. Three main measures for doing this can be identified based on the interviews with the grid operators:

- Make the permission process for grid expansions more structured and agile, where, for example, subprocess are run in parallel to a greater extent.
- Proactive grid planning, e.g. work with project portfolios that show what capacity is available in the long and short term.
- Higher prioritization of electricity grid infrastructure in the political debate.

The uncertainties connected to the grid concession procedure, mentioned by both (Tenggren *et al.*, 2016) in the literature and by the grid operators in the interviews, need to be resolved to facilitate grid expansions. A clearer framework, than today, defining which stakeholders should be included in the procedure would facilitate communication and the handling of conflicting interests among stakeholders. An improved coordination between the different court proceedings could also contribute to a smoother and faster concession procedure. A higher

prioritization of grid infrastructure in the political debate could be an enabling factor for this type of changes to start happening.

As mentioned in the interviews and literature, grid for specific demands, like industry establishments, will not be built on speculation meaning that the uncertainties in how the electricity demand will develop in Sweden up until 2045 will put pressure on the grid operators. The industry will also need to realize that good communication in advance may be needed to meet increased electricity needs, and as (Thelin, 2020) describes, the time when it was possible to sign a new contract for large connections immediately is now past. Now this needs to be preceded by investigations about available capacity.

Electrification within the transport, residential and service sectors differs from the industry sector by giving rise to a more dispersed increase of electricity demand. The electrification rate in these sectors is in practice impossible to confirm in advance, which means that electricity grid expansion based on speculations cannot be avoided. Both the interviews with the grid operators and Obel *et al.* (2020) gives the impression that electrification within the transport sector will not be very problematic to meet from a grid perspective, at least not in a short-term perspective. Obel *et al.* (2020) further describes that problems might arise in local grids in 10 years, due to electrification of transports. When it is not possible to avoid the electricity grids being built on speculation, the importance of making good forecasts increases, which several of the measures discussed could contribute to.

8. Conclusion

The national scenario analysis shows the lowest prediction of annual electricity demand in 2045 of 171 TWh and the highest prediction of 207 TWh. It can be concluded that decarbonisation within industry and transport sectors in order to reach the climate targets in 2045 is a driver for electrification. The results also indicate that there might be a larger electrification potential than the national scenarios predict, if the electrification route is chosen above conversion to other biofuels.

It is challenging to conclude what regions will have the largest increase in electricity demand due to the uncertainty of which decarbonisation routes that will be taken. However, large electrification potentials have been identified in the four investigated regions where analysis of Västra Götaland shows a quite extreme electrification potential, mainly driven by industries. The electrification potential identified in:

- Norrbotten is estimated to 10.7 TWh, mainly due to decarbonisation of in industries.
- Västra Götaland is estimated to 21.2 TWh, where increases in all investigated sectors contributes to the increase.
- Stockholm is estimated to 10.7 TWh and in Skåne to 6.3 TWh mainly due to electrification of the transport sector and urbanisation.

Reinforcements in the grids will be needed in all investigated regions if the electrification potential is to be realised and if capacity shortages are to be avoided. The lack of capacity in the transmission grid is the main problem. The grid operators have an optimistic belief in being able to meet the electrification, as long as new demands are communicated with reasonable anticipation.

A common perception among the grid operators is that the permit process for new power lines needs to be sped up in order to facilitate for the grid operators to be able to meet the electrification. The procedure also needs to be clarified in order to avoid conflicting interests among stakeholders. Better communication and transparency in scenario and prognosis work is also mentioned as a factor that would facilitate the grid planning process. Electrification in the industrial sector is concluded to be the major challenge from an electricity grid perspective mainly due to industry having shorter lead times than grid expansions. To cope with the decarbonisation of industry, the decarbonisation route soon needs to be chosen. Three different ways are seen to achieve climate-neutral industries by 2045.

- If the permission process for electricity grid expansion does not change and the industry is to choose the electrification route, this needs to be decided before 2030 in order for reinforcements in the electricity grid to be ensured before 2045.
- Speed up the permit process to allow shorter lead times for power grid expansions.
- The industry choose another route for decarbonisation than electrification.

The overall conclusion is that new approaches for expanding the electricity grid will be required if large-scale electrification is to be a key factor in achieving the climate goals in 2045. It can also be concluded that practically all involved stakeholders can contribute in different ways to meet the challenge of providing sufficient grid capacity when new electricity demands arise.

9. Further studies

Ideas interesting to study that are not covered in the thesis have arisen during the thesis work. Since the work was delimited from investigating the electricity system from the supply side, the system perspective is lacking to some extent. An investigation of how electricity production could change could contribute with interesting findings to supplement the results of the thesis and provide a better overall picture of what changes need to be made in the electricity system.

The potential of an increased electricity demand in industries already electrified or using biomass are missed out and have not been mapped out in any of the studied scenarios. New type of industries also show a significant electrification potential that could be deeper investigated. Therefore, a study of these companies would bring insights on the potential of an increased electricity demand from those companies.

Price trends for electricity and other energy carriers are very likely to have a significant impact on the energy use in the future energy system, e.g. tax levels on fossil fuels and CO₂-eq emissions. An analysis of possible developments of energy prices and supply reliability for different energy carriers could, therefore, provide exciting inputs to the questions answered in the thesis. The availability of biomass could affect the extent of electrification that will occur, where limited access can lead to greater electrification, and good access could lead to a transition to more bioenergy.

During the interviews with the grid operators, both Ei and Business Sweden, was mentioned several times. It would be interesting to interview Ei to add more perspectives and get a deeper understanding of the concession process. It would also add perspectives to interview Business Sweden who are trying to establish new industries in Sweden to understand how they see the situation.

The results from the thesis shows the importance of analysing the electrification potentials at the regional level. It would, therefore, be interesting to investigate more regions to be able to sum up the demands, to see how it differs from the national scenarios. Example of regions that are interesting for further studies is Gotland due to its large industrial emissions or some of the regions where considerable population growth is predicted.

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Appendix A1

Interview questions for industries

Current situation:

Large industries that will have to make a decarbonize their production in order to achieve the climate target set for 2045 have been identified. Identification has been made by looking at which companies have high CO₂-eq emissions today and thus are likely to need to do a fuel conversion.

1. We therefore wonder from what types of processes your current CO₂-e. emissions can be derived?

Above all, we are interested in processes that can be converted from fossil fuels to electricity and how large the electricity demand possibly can be by 2045.

Conversion:

2. What plans are in place to switch these processes to biofuel, electrification, CCS, or any other alternative to become fossil-free or carbon neutral?
- We are interested in orders of magnitude around both energy quantity and power and when the transition is believed to take place.

Challenges:

3. What do you see as the significant problems in phasing out fossil fuels?
4. Do you see any problem with applying for increased power requirements in your plants in the future? For example, the time perspective.

Appendix A2

Analysis data for industries in Norrbotten.

SSAB EMEA Luleå

SSAB EMEA, located in Luleå, is an integrated iron and steel production plant with a blast furnace (SSAB Luleå, 2018).

The majority of today's CO₂-eq emissions comes from the use of coal and coke (SSAB Luleå, 2018). SSAB is part of the project HYBRIT, aiming at a fossil-free steel industry. The plan for reaching fossil independence is to replace the blast furnace ironmaking with a direct reduction process, using hydrogen and fossil-free electricity instead of fossil fuels (HYBRIT Development AB, 2017). Hydrogen will be produced through electrolysis (Swedish Energy Agency *et al.*, 2018) which is an electricity-intensive process. It is estimated that 3 488 kWh electricity per tonne of crude steel is needed for the direct reduction route (HYBRIT Development AB, 2017). Based on the pre-study and the time plan for the HYBRIT project the electricity demand in Norrbotten is estimated to increase with approximately 9 TWh up until 2045 (HYBRIT Development AB, 2017; Swedish Energy Agency *et al.*, 2018). Table 18 shows the estimated implementation stages in the HYBRIT project.

Table 18: Overview of the HYBRIT's project phases together with the estimated increase of electricity demand.

Project phase	Year (HYBRIT Development AB, 2017)	Production [tonne/year] (Swedish Energy Agency <i>et al.</i> , 2018)	Operation times (Swedish Energy Agency <i>et al.</i> , 2018)	Estimated yearly electricity demand (TWh)	Estimated power demand (MW)
Test		-	-	-	
Pilot	2020 - 2025	1-10 tonne/h	Campaigns	-	-
Demo	2025 - 2035	250 000 – 500 000	Continuous	1 – 2	100-200
Production	2035 -	500 000 - 2 500 000	Continuous	2 – 9	200-1000

Lulekraft

Lulekraft AB is a combined heat and power plant that is integrated with SSABs steel production (Lulekraft AB, 2019) and is therefore categorised by the Swedish Environmental Protection Agency as part of the iron and steel industry.

Lulekraft AB uses excess gases from steel making process to generate hot steam for electricity and heat production (Lulekraft AB, 2019). Replacement of the blast furnace ironmaking at SSAB with a direct reduction process will eliminate the supply of excess gases to Lulekraft AB. Excess gases could possibly be replaced by excess heat from electrolysis for hydrogen production (M. Nordlander, 2020). The use of excess heat would mean that no significant change in electricity demand can be predicted.

LKAB

LKAB is a company within the mineral and mining industry producing iron ore. The company have three mines in Norrbotten; Svappavaara, Kiruna and Malmberget. Svappavaara is an open-pit mine while Kiruna and Malmberget are underground mines. (LKAB, 2019)

LKAB's ambition for 2030 is to reduce their CO₂-eq emissions and energy use by biofuel conversion of fossil fuel ovens, and electrification of mining operation processes. The long term goal is to become fossil-free until 2045, but the roadmap is not yet developed, and there are therefore uncertainties in what measures will be taken. The electricity demand is believed to increase, but the most significant uncertainties are production volumes, development of new technology and how the HYBRIT project will affect LKAB. (Frohm, 2020)

Assuming today's conditions, pelletising plants stand for approximately 80–90 % of today's emissions due to the combustion of coal, natural gas and fuel oil (Frohm, 2020). The current plan is to convert to bio-oil, which would not mean a significant increase in electricity demand (Frohm, 2020). However, there is ongoing research on conversion to plasma furnaces which could lead to an increased electricity demand, but there are uncertainties if this will be realised and no date can, therefore, be set (Swedish Energy Agency *et al.*, 2018; Frohm, 2020).

According to (Lindén and Thureborn, 2019) the electricity demand could increase with 32 kWh per produced tonne of pellets by replacing the current heating process with heating via plasma. The finished production volumes per site are (LKAB, 2019):

- Kiruna 14.7 million tonne
- Malmberget 9.6 million tonne
- Svappavaara 3 million tonne

Assuming today's production volumes would result in an electricity demand:

- Kiruna 470.4 GWh, 58.8 MW
- Malmberget 307.2 GWh 38.4 MW
- Svappavaara 96 GWh, 12 MW

As a part of a project called *Sustainable Underground Mining (SUM)*, an electrification strategy exists for internal transports linked to mining operations (Sustainable Underground Mining, no date; Frohm, 2020). Through the project, LKAB is working with other players with automatisisation and electrification of operations in the mines, which will lead to the phasing out of fossil diesel (Sustainable Underground Mining, no date; Frohm, 2020). Today's total use of fossil diesel for mining operations is around 114 GWh (Frohm, 2020). Electrification would lead to an increased

electricity demand of approximately 44 GWh¹. Today, LKAB do not see any problem with grid capacity due to their planned electrification of the mines (Frohm, 2020).

¹ Assuming an efficiency of 35 % for diesel engines and 90 % for electric engines (Paraszcza *et al.*, 2014)

SMA Mineral AB Luleå

Luleå Kalkverk, located in Luleå, is a company within the mining and mineral industry. It is owned by SMA mineral and is located on SSAB's industrial site, producing limestone and quicklime (SMA Mineral, no date a).

The carbon dioxide emissions from Luleå Kalkverk's site comes from combustion in burners fired by coke oven gas (L. Nordlander, 2020) and from chemical reactions when the limestone is undergoing dissociation (SMA Mineral, no date b). The emissions from chemical reactions when the limestone is undergoing dissociation is according to Ecofys *et al.* (2009), approximately 0.785 tonnes of CO₂ per tonne lime. The combustion emissions from the fuel is approximately 0.15 tonne CO₂-eq per tonne lime (L. Nordlander, 2020). Thus, total emission is approximately 0.94 tonne CO₂ per tonne lime.

Today's production volume is approximately 120 ktonne quicklime per year (L. Nordlander, 2020). During the interview, L. Nordlander (2020) refers to the EU BAT document for lime production to make an estimate of the electricity demand as a result of the electrification of their processes². Based on today's production volume, this method results in the estimation that electrification of the burners would lead to an annual electricity demand of 106.7 GWh.

Electrification of burners using electric heating would not eliminate emissions from chemical reactions, corresponding to 94.2 ktonne CO₂. Using CCS to reduce these is estimated to lead to an increased annual electricity demand of up to 28.3 GWh.

CCS combined with electrification of burners would, therefore, lead to an increased demand of 135 GWh/year in total. Only using CCS to reduce the total current emissions of 112.8 ktonne CO₂ would lead to an increased electricity demand of 33.8 GWh.

Research and development of new technology in combination with available capital for investment in new technique is needed before electrification or CCS is implemented (L. Nordlander, 2020). It is therefore not possible to set a date for when the conversion will happen (L. Nordlander, 2020). Another possible solution that would be more economically justifiable is to modify the current ovens to use hydrogen as fuel, but a competitive hydrogen production is needed (L. Nordlander, 2020). The electricity demand will be about the same for both techniques (L. Nordlander, 2020).

² Schorcht *et al.* (2013) states in the EU BAT document for lime production that 3.2 GJ/tonne heat energy is needed for the lime to undergo dissociation.

Appendix A3

Analysis data for industries in Västra Götaland.

Preem AB - Lysekil and Göteborg

Preem is a company within the refinery industry and have two refineries in Västra Götaland. An oil refinery is located in Lysekil, and a hydro skimming refinery is located in Gothenburg (Preem, no date b, no date a)

Preem's goal is that their refineries will have net zero emissions of CO₂ by 2040 and that the entire value chain will have net zero emissions by 2045 (Jannasch *et al.*, 2020). To fulfil this goal, Preem has several ongoing projects researching the possibilities to produce renewable fuels such as HVO, lignin and biomass that can be upgraded (Jannasch *et al.*, 2020). Preem is also researching the potential for producing electro fuels and implement CCS (Jannasch *et al.*, 2020). If these projects were to be implemented on a large scale, it would lead to an increased demand for electricity and hydrogen (Werner *et al.*, 2019).

Preem and Vattenfall have a joint project where they are doing a feasibility study for establishing an electrolyser for hydrogen production with a power demand of around 20 MW at the refinery in Gothenburg to replace parts of the hydrogen production that is currently done with the help of natural gas (Werner *et al.*, 2019). The plan is to have the hydrogen production in operation by 2024 (Jannasch *et al.*, 2020).

Jannasch *et al.* (2020) has studied opportunities for implementation of P2X technologies in Västra Götaland. The study shows that Preem may need to invest in two hydrogen plants, one in Göteborg with a power demand of 100 MW and one in Lysekil with a power demand of 400 MW by 2035 in order to reach the climate targets set. According to Werner *et al.* (2019), it is technically possible to build the electrolyzers, but the challenge is to assure the capacity for the electricity that would be needed operating the electrolyzers.

Borealis AB - Stenungsund

Borealis AB is a company within the chemical industry manufacturing polyethene. They produce a wide range of products in their cracker ovens fueled by LPG.

The majority of the Borealis CO₂e emissions comes from producing olefins by cracking hydrocarbons in an endothermic process, called “steam cracking process”. The cracking furnaces are fired by methane and hydrogen which are byproducts generated in the cracking process.

There are several alternatives for decarbonisation current production processes (L. Pettersson, 2020):

1. Electrical cracker furnaces, as a part of a European multi-partner project called “Cracker for the future”, the feasibility of direct electrification of the cracking furnaces are investigated. Perhaps a commercial solution is available around 2030.
2. Fuel conversion of the cracking furnaces to hydrogen, e.g. hydrogen from electrolysis using renewable electricity.

Complete decarbonisation through electrification, either directly or via electrolysis, is estimated to lead to an increased electricity demand of around 500-600 MW. This is however seen as unlikely, and a more moderate electrification corresponding to around 200-300 MW. Even if the process is electrified there is still a need for taking care of a residual methane stream that is generated in the cracking process, which calls for even higher electrical demand, say another 100 MW.

3. Implementing CO₂ Capture for storage or utilization:

There is ongoing research regarding CCS and CCU. Implementing the CCU process for producing methanol is one option. This would require around 500 MW in extra electricity capacity to be used for; 1) capture around 600 ktonne CO₂ and 2) produce associating hydrogen coming from electrolysis. By only go for CCS, the electricity demand is lower, say around 100 MW more.

4. Bio-based feedstocks:

Bio-based cracker feedstock is also being evaluated as a way to reduce the CO₂-emissions. However, the availability of such feedstocks are limited, and it is unlikely that it can replace all fossil-based feedstock cracked today. The good news is that such a transition has a minor impact on the electricity demand, albeit some hydrogen might be needed for pre-treating the bio-feedstock with hydrogen.

5. Chemical recycling:

Chemical recycling means that plastic waste can be re-used as feedstock for producing olefins. Regardless of which technology to be selected, the process is exothermic and require lots of heat. In order to reduce CO₂-emission for such a unit, electrical energy is one way forward. It is very difficult at this stage to estimate energy use for a chemical

recycling plant, but another 500 – 1 000 MW, depending on technology selected and how much of the feedstock needs this will cover, is a first guess

The most likely scenario going forward will be a combination of the above-mentioned opportunities. In order to be successful in reducing CO₂ emissions in Borealis and the Chemical Industry, it requires more renewable electricity and grid extension as well as increased robustness/reliability. It also requires a competitive electricity price. Lead times needs to be reduced for grid extensions, and the permit process needs simplification and acceleration, otherwise the reductions will not materialize in time

St1 Refinery AB - Gothenburg

St1 Refinery AB, located in Gothenburg, is a company within the refinery industry. Their production of fuels equals to around 20 % of the fuel needed for transports in Sweden. One third, 660 GWh, of the heat that is generated at the site is delivered to Gothenburg DH system (St1, 2020).

The organisation of St1 have an ambition to reduce their CO₂-eq emissions both from refinery processes and the products produced in order to become CO₂-eq neutral until 2045 (Karlsson, 2020). St1 are currently looking into several solutions to reduce the CO₂-eq emissions and sees electrification as the enabler (Karlsson, 2020). St1 is primarily focusing on decreasing the CO₂-eq emissions from the final use of their products, because only a minor part of the emissions can be connected to the production process (Jannasch *et al.*, 2020; Karlsson, 2020). Due to this, St1 is working with transforming their production of fossil fuels into the production of biofuels and electro fuels (Jannasch *et al.*, 2020; Karlsson, 2020). This transformation will lead to an increased demand for electricity since the production of biofuels generally, and synthetic fuels especially are electricity-intensive (Karlsson, 2020). Currently St1 are planning to set up a CCU project during 2020 at a cement production in Finland where they look into the opportunity to use CCU and produce methanol from captured CO₂-eq and hydrogen produced from green electricity (Karlsson, 2020). Karlsson (2020) believes that it is reasonable to believe that a scalable implementation of the technique will happen between 2025-2030.

A report published by Rise has investigated what possible electrification could be implemented at St1. Hydrogen production is planned to be increased, and a new hydrogen plant is ready in 2020, leading to an increased electricity demand of 1-2 MW (Jannasch *et al.*, 2020). The new hydrogen production via electrolysis is planned to replace hydrogen production from natural gas. There is also a biorefinery that will be finished in 2022, leading to an additional demand of 3-4 MW (Jannasch *et al.*, 2020). For full-scale transformation into bio- and electro fuel production at the refinery site, the electricity demand could increase by 300-350 MW (Jannasch *et al.*, 2020). According to (Karlsson, 2020), 350 MW should definitely be seen as a theoretical high upper limit of what the electricity demand can become if utilising all potential CO₂.

The price of electricity is seen as one important factor determining what will be implemented and when. Energy prices cannot become too high since the company still needs to make a profit. St1 does not believe that there will be a problem, from a grid perspective, to implement the new processes that require electricity up until 2030 but that there is a risk that power shortage will be a problem after 2030. The risk is due to a combination of the long processes to increase the capacity in the grid and that the electrification rate will increase. (Karlsson, 2020)

Cementa AB - Skövde

HeidelbergCement is right now aiming for a full-scale solution by 2024 to decarbonise a large part of their manufacturing process and in Norway. The site in Skövde is a landlocked medium-sized plant. Cementa and its parent company HeidelbergCement are as a first step focusing on implementing new carbon capture technologies on their larger sites. Focus for the Skövde plant is instead on substituting coal with biobased fuels in the heating process and substituting limestone-based clinker by recycling other raw materials with smaller CO₂-footprint. The future chosen way to go will be heavily dependent on the competitive situation for the European cement industry alongside the development of carbon capture opportunities in our region. (Cementa AB, 2020)

Vargön Alloys - Vännersborg

Vargön Alloys, located outside of Vännersborg, is a company within the ferroalloy industry manufacturing ferrochrome (Jansson, 2020). Vargön Alloys had carbon emissions corresponding to 165 ktonne CO₂-eq during 2018, which give a carbon footprint of 1.59 tonne CO₂/tonne alloy (Jansson, 2020). According to the latest LCA (Life cycle assessment), made by ICDA (International Chromium Development Association), Vargön Alloys uses 27 % of CO₂/tonne alloy compared with the eight greatest competitors in the business (Gediga and Sandilands, 2011; Jansson, 2020).

The CO₂-eq emissions comes from a pyrometallurgical process where coal and coke are used as a reductant to reduce chromite ore to metal. The company is almost fully electrified and recover approximately 45% of its electric energy to district heating through the company's heat recovery system. Through a company agglomerate Vargön Alloys delivered 192 344 MWh of heat to Trollhättan and Vännersborg in 2018. (Jansson, 2020)

Two routes are possible to eliminate the fossil emissions further, either replace the fossil reductant with bio-coal or the use of CCS. The CCS solution is seen as the most likely final solution to be carbon dioxide neutral. However, this will require a lot of investments and more research before it can be implemented in the company's process. There are no decisions taken yet about the CCS, but the company follows the European ferro-alloys associations (EUROALLIAGES) roadmap to sustainable production by 2050. (Jansson, 2020)

To reduce the fossil emissions, bio-coal can replace some of the fossil reductants currently being used. The company do not think it will be possible to change the fossil reductant entirely with bio-coal due to biomass might become a limited resource in the future. (Jansson, 2020)

There are currently four electric furnaces at Vargön Alloys, one large furnace with the maximum power of 50 MW, one mid-size furnace with the maximum power of 30 MW and two smaller furnaces with the maximum of 15 MW. The production Vargön Alloys have no plans of constructing additional furnaces. However, there is the potential to utilise more of the capacity of the existing furnaces. Currently, not all furnaces are used, which means that only 81 MW is needed, and thus there is a potential to increase the demand by 30 MW with existing furnaces. (Jansson, 2020)

Vargön Alloy does not believe that applying for an increased power demand would cause any problems. Their location is believed to be beneficial because of the proximity to hydroelectricity production. (Jansson, 2020)

Perstorp Oxo AB - Stenungsund

Perstorp Oxo AB, located in Stenungsund, is a company within the chemical industry. The industry is part of the industry cluster in Stenungsund with a feedstock supplied by surrounding companies.

Today Perstorp has no plans on electrifying their processes. Their focus is on the downstream process instead of producing their own feedstock. Instead, they will buy climate-neutral feedstocks. (Jannasch *et al.*, 2020)

Perstorp is part of different R&D projects where different types of electrolysis is investigated, but there is no concrete plan of investing in and running any electrolysis process (Jannasch *et al.*, 2020)

Appendix A4

Analysis data for industries in Stockholm.

Nynas AB - Nynäshamn

Nynas AB, located in Nynäshamn, is a global company within the refinery industry. The company focuses on a niche market and are specialised on naphthenic speciality products and bitumen. (Nynas AB, no date a)

In the past, they have reduced their CO₂ emissions by installing a cogeneration plant to produce steam via biofuels, and they have converted their hydrogen production from naphtha to natural gas. (Nynas AB, no date b)

Upon contact, the company declined to be interviewed, but stated that they are following the development of new technologies, e.g. hydrogen production using electrolysis (Nynas AB, 2020). No further information could be obtained about if or how Nynas AB is planning to decarbonise its refinery. In December 2019, it could be read that Nynas AB filed for company reorganisation because due debts could not be paid (Nynas AB, 2019).

Appendix A5

Analysis data for industries in Skåne

Höganäs Sweden AB - Höganäs

Höganäs Sweden AB, located in Höganäs, is a company within the steel industry producing metal powder for other industries (Höganäs AB, 2019). Around 70 % of the CO₂ emissions at Höganäs can be allocated to the use of fossil coal and fuel is used in different production processes, where natural gas stands for the majority of the emissions followed by LPG diesel and gasoline.

Höganäs AB is primarily looking into techniques based on biomass for decarbonising their site in order to reach the 2045 climate goals (M. Pettersson, 2020). The main source of CO₂ emissions is the sponge iron process, but the process is not possible to electrify since the material would not get the same properties (M. Pettersson, 2020). Höganäs AB is currently doing research on replacing the coal with bio-coal (Höganäs AB, 2020).

There is a possibility to electrify other processes at the site, but there are no concrete plans if or when this could happen (M. Pettersson, 2020). M. Pettersson (2020) states based on an estimate calculation using current production volumes that electricity demand could increase by around 60 GWh if today's hydrogen production were to be electrified, leading to a power demand of an additional 7 - 10 MW. Converting fossil fuel use to electricity could lead to an additional 150 - 200 GWh of electricity demand and a power demand of 10 - 20 MW (M. Pettersson, 2020). The electricity demand can increase even more if CCS or CCU is implemented, but Höganäs does currently not see an implementation as likely (M. Pettersson, 2020).

Norcarb engineered Carbons - Malmö

Norcarb engineered Carbons located in Malmö is a company within the chemical industry manufacturing carbon black as the main product (SSG, no date). District heating, electricity and steam from excess heat are by-products. Heavy fractions of oil are used as input in the manufacturing process (SSG, no date). Norcarb engineered Carbons is part of the international company group Orion (Orion Engineered Carbon, 2019).

Orion's, which Norcarb engineered carbons is part of, plans to reduce the GHG emissions by increasing the amount of carbon they extract from the feedstock. The hope is to reduce the CO₂-eq emissions per produced tonne of carbon black by 5 % by 2029 compared to 2014. They are also focusing on increasing their energy efficiency by 2 % until 2029 compared to 2014. (Orion Engineered Carbon, 2019)

The response given by a Norcarb representative was that since the feedstock is either fossil coal or fossil oil, it is not possible to decarbonise the production via fuel conversion (Norcarb Engineered Carbons AB, 2020). Therefore it is assumed that CCS would be a possible solution and would lead to an increased energy demand of approximately 27 GWh.

Nordic sugar AB - Örtofta

Nordic sugar AB, located in Eslöv, is a company within the food industry manufacturing sugar at one of the largest sugar production sites in Europe. The company is aiming at becoming fossil-free until 2050. The production is seasonal and runs continuously for approximately four months, from Mid-September to mid-January. (Nordic Sugar, no date)

The main source of CO₂-eq emissions is from steam production using natural gas as input fuel. The natural gas demand is 110-120 MW, where the steam is used for processes such as evaporation and drying. Steam is also used for the site's own electricity production with two turbines that can meet the electricity demand needed to keep production going. In addition to its own production, there is a power purchase agreement of 8 MW, meaning that they can balance electricity use between its own generated electricity and purchased electricity. Quicklime is also produced at the site and used in a purification process. Combustion with coke is used for the quicklime production, meaning that this process also is a source of CO₂-eq emissions. (Dahlgren, 2020)

Nordic Sugar has previously worked with implementing energy efficiency measures to reduce its energy use and is now facing a phase-out of fossil fuel use. This phase-out is not believed to lead to any significant increase in electricity demand. A gradual transition to biogas is considered more likely. However, a relocation of a refinery, moving from Arlöv to Örtofta, will increase the electrical power demand at the site by approximately 1.5 MW by 2022. (Dahlgren, 2020)

They see no immediate risk of not being allowed to increase their electrical power requirements, partly because of the facility being relocated frees up grid capacity at its current location and they can increase their own electricity production by optimisation. (Dahlgren, 2020)

Perstorp speciality Chemicals AB - Perstorp

Perstorp Specialty Chemicals AB located in Perstorp is a company within the chemical industry manufacturing polyols, formates, organic acids and formaldehyde (Perstorp Specialty Chemicals AB, no date).

No response was received when attempting contact, and therefore, no interview could be conducted. No further information could be obtained about if or how Perstorp speciality Chemicals AB is planning to decarbonise its factory and what impact that would have on the electricity demand.

Boliden Bergsöe AB - Landskrona

Boliden Bergsöe AB, located in Landskrona, is a company within the metal industry recycling lead-acid batteries. (Boliden, no date).

Boliden states in their Environmental report that there are several ongoing research projects about reducing their CO₂-eq emissions from smelters. The different pathways that are mentioned are fuel conversion to hydrogen or biofuels, CCS-solutions and energy efficiency measures. (Boliden, 2020)

Boliden Bergsöe is a heat-intensive industry where the CO₂-eq emissions are connected to the use of natural gas for heating, coke as reduction material and heating, plastics being combusted and coal used as reduction material. A mechanical separating plant was completed during 2019 that will separate PP-plastics from lead batteries before combustion and reduce the CO₂ emissions with 25 %. (Arnerlöf, 2020)

Replacing the natural gas is possible since it is not used as feedstock. Natural gas used (Arnerlöf, 2020):

- in final combustion can be replaced by biogas.
- to hold the temperature of the molten lead are under research and can probably be electrified. However, there are some technical limitations. There is a need to increase and decrease the temperature fast.
- to preheat air can be replaced by electricity. However, there are some technical limitations due to the high airflow.

Implementation of electrification measures would mean that approximately 25 GWh of natural gas use is theoretically possible to convert to electricity. Today, there are no problem connected to the supply of electrical power demand, and they have not got any intentions from their electricity grid operator that so would be. (Arnerlöf, 2020)

The coke is more challenging to replace than the natural gas since it is used for reduction in the products. Bio-coal is a possible solution, but is right now seen as an immature technology that needs further research before it is implemented. Another possible technique is to use hydrogen for the reduction need. (Arnerlöf, 2020)

Kemira Kemi AB - Helsingborg

Kemira Kemi AB, located in Helsingborg, is a company within the chemical industry manufacturing chemicals for different industry applications (Kemira, no date). Production processes are highly exothermic, and large amounts of energy are recovered every year (Gunnarsson, 2020). Recovered energy is used by Kemira Kemi AB, and the excess is sold to the companies within the industrial park (Gunnarsson, 2020). Excess heat is also used for district heat production, supplying the city of Helsingborg (Kemira, 2020).

Kemira AB have a continues production during the year and produce over 50 % of their electricity demand on-site. The majority of the CO₂ emissions comes from the use of natural gas, where around 60 % are used for combustion and 40 % as feedstock in the process. The Kemira company group have set a goal to reduce their emissions from their own energy production and emissions based on purchased energy GHG emissions with 30 % by 2030 and to reach climate neutrality by 2045. (Gunnarsson, 2020)

Kemira is investigating several options to reduce GHG impact, for example, fuel conversion or sourcing of low-carbon or carbon-neutral energy. They are also focusing on making their processes more energy efficient. Today it is not possible to predict how the electricity demand can change. (Gunnarsson, 2020)

Appendix B1

Interview questions for grid operators

Discussion of the current situation and our results:

1. What are your comments on the potential electrification that we identified in our regional analysis, and is it in line with what you believe?
2. How good conditions do you think there are to meet the expected electrification in Region **X**?
 - I What challenges do you consider to be for increased electrification in each sector?
3. Is **X** an area where there is generally plenty of capacity left, and does it look different in the region?
 - I Has the demand for electricity increased in recent years?
 - II Are there plans for expansion to increase network capacity?
4. Is there a risk of capacity shortage in **X**?
 - I Is the risk greater in any part of **X** and is the risk greater in transmission, regional or local grid?
 - II If there is a risk, how do you work to prevent this from happening?

Discussion of planning and expansion of the electricity network

5. What basis is required to decide whether to build a new pipeline?
 - I Could electricity network companies do anything to contribute to accelerated electrification?
 - II Do you have the information needed to make long-term forecasts, or is there something missing?
6. How is the cooperation between electricity network companies, electricity producers and electricity users when forecasts are made?
 - I Is cooperation and contact ongoing, or is it especially within specific projects?
7. How well can the lead times be predicted to meet the need for increased electricity use by an individual customer?
 - I What do you consider to be the bottleneck/bottlenecks in the expansion of the electricity grid?
 - II What would it take to remove these bottlenecks?

^a **X**- The investigated region were inserted for all interview except with Svk. With Svk all regions where inserted.

8. Statement from the industries perspective:

Electricity grid operators cannot provide rapid information about new connections and cannot guarantee the reliability that the industry wants guaranteed, and this leads to the grid operators, largely controlling the rate of electrification of industry.

What is your view on this statement?

9. Is there any more aspect that you think is important to highlight?

Appendix B2

Interview summaries for interviews with grid operators

Interview with Vattenfall Eldistribution AB with focus on Västra Götaland and scenarios.

Three interviews were held with Vattenfall Eldistribution AB. The interview about the situation in Västra Götaland was held with two persons, one with knowledge about the region and one with knowledge about scenarios. The interviews about Norrbotten and Stockholm was held with one person with specific knowledge about the region.

Interview with Vattenfall Eldistribution AB

Vattenfall Eldistribution AB (2020b) states that variations in electricity and power demand has mainly been connected to weather variations. There have been relatively few new large applications for electric power from industries during the last 40 years. The applications have traditionally been in sizes of around 15-20 MW. But the future demands that are discussed within the industries in the region are of a different proportion.

Vattenfall Eldistribution AB (2020b) do not believe that the electricity demand in the residential and service sector will decrease. Instead, it is believed that an increased demand due to population growth will be counteracted by energy efficiency measures and that the power peaks can be managed with different smart solutions. For example, electrification of the transport sector is believed to result in a significant increase in energy, but the charging can through smart control be scheduled to low loads hours. Vattenfall Eldistribution AB (2020b) sees the increased electricity demand that comes with urbanisation and electrification of the transport sector as a relatively slow and continuous. This slow and predictable development means that Vattenfall Eldistribution AB (2020b) believes that the demand can be met. However, the situation is very different between regions. For example, people are moving from the countryside in Norrbotten while there is population growth in the urban areas. The consequence of this is that there will be fewer customers per kilometre grid and that comes with a higher cost per customer.

Vattenfall Eldistribution AB (2020b) assess the current situation in the region as yellow/green. It is hard to assess the situation until 2045. The major problem for meeting electrification and higher power demands is stated to be lead times due to how the concession application processes are formed today. In combination with long lead times, grid operators also need to be able to justify why they are building a new power line. This means that the grid operators cannot be proactive when expanding the grid. These factors are reasons to why capacity shortage can occur. If all identified electricity demands would be realised it would require the grid capacity to be doubled. Realisation of all potential electrification in Västra Götaland can be seen as unlikely. However, Vattenfall Eldistribution AB (2020b) believes that all applications will not come at the

same time, which will increase the possibility to manage them. A large scale electrification would need to be managed either by flexibility in the industry or a quicker and more efficient concession process. It is, however, important that the concession process remains democratic and that all stakeholder gets to share their opinions.

Vattenfall Eldistribution AB (2020b) believes that the grid development historically where quicker and the industries needed longer time for establishment. The divergence in lead times have become a problem since concession for grid expansions are taking a longer time, and industrial establishments are quicker. To reduce the lead times for grid concessions, Vattenfall Eldistribution AB (2020b) believes that questions regarding the electricity grid infrastructure needs to get higher priorities in society to enable the electrification of the society.

Communication between all stakeholders is also mentioned as a very important factor for the development of the grid. The communication with Svk is considered to be good. Contact takes place both through the formal applications for grid concession but also through continues planning meeting where they discuss the development. Vattenfall Eldistribution AB (2020b) mentions that the communication with the municipalities could be improved. For example, information about local development could be collected and compiled by the regional government to make it easier to get an overview and make the process more standardised.

Interview with Vattenfall Eldistribution AB with focus on Norrbotten

Vattenfall Eldistribution AB (2020c) says that the current situation in Norrbotten is good in general when it comes to capacity. The region benefits from having large scale electricity production. It is only in the coastal area with Skelefteå, Luleå and Piteå that the upper limit for transmissions capacity is approaching. This is mainly due to the establishment of electricity-intensive operations such as Facebook, Bitcoin mining and Northvolt.

When discussing the results from the industries, the identified possible power demand in the coastal area around Luleå is considered reasonable. Vattenfall Eldistribution AB (2020c) believes that the electricity demand could increase a lot in the inner parts of Norrbotten as a result of large-scale electrification of mining operations. It is mentioned that the location for HYBRIT is not determined, and that it is therefore not certain that it will end up in Luleå. Another possible location is Malmfälten in the area of Gällivare and Kiruna. Due to its size, HYBRIT most likely will be connected to the transmission grid owned by Svk, and therefore it might be a problem if the establishment of HYBRIT will be in Malmfälten since the transmission grid does not exist that far north.

One important factor to take into consideration is that all of the sites that Nord pole shows as possible locations cannot be realised at the same time, e.g. Helicopter Airbase and Svartbyn.

Vattenfall Eldistribution AB (2020c) mentions that there are uncertainties on whether the electric power demand within the residential and service will increase or not. A large proportion of the electricity demand in residential & service in Norrbotten is connected to the heating demand. For example, the electric power demand is 30 % lower in Luleå today compared to 30 years ago. This is due to energy efficiency measures in buildings and conversion from direct electric heating to, e.g. district heating and heat pumps. Vattenfall also believes that there still is potential for more energy efficiency measures in the residential & service sector, especially in Norrbotten. Therefore, only a minor increase in electricity demand are predicted in the coastal region, and that there is more likely to be an increase in Stockholm that will have a larger population growth.

The transport sector will increase the energy demand, but the predicted 200 GWh. Vattenfall Eldistribution AB (2020c) sees it as difficult to justify investing in flexibility for electric car charging in Norrbotten. Unlike large city regions, where problems with capacity shortage is more acute, in Norrbotten there is generally still capacity to utilise. Vattenfall Eldistribution AB (2020c) thinks it would be difficult to find a business model for regions with available grid capacity and surplus production and that no one will, therefore, be willing to invest in flexibility. Based on the conditions in the region, it would probably not be socially economically viable either.

Capacity shortage only appears when the grid expansions are too slow and cannot keep up with the expansion plans. It is a risk that capacity shortages will occur everywhere if the grid planning process does not become more proactive. For example, the grid concessions could be prepared

proactively. It takes around ten years to get line concession and build the grid infrastructure, which is way too long for a new type of industries that have shorter lead times for establishment than they may have historically had. Vattenfall Eldistribution AB (2020c) thinks that the lead time for a grid expansion needs to be reduced to around five years. If the lead time is reduced, it also reduces the risk of having to speculate when expanding the grid. It also mentioned that, if a capacity shortage is risked, it will only require a shorter expansion of the grid, and therefore, the grid concession process will be shorter. The grid has in the past been developed on speculations that have been more accurate and have been about smaller demand. Vattenfall Eldistribution AB (2020c) mentions that grid expansions for industries such as HYBRIT and Datacentres, which is of an extreme magnitude, will never be done on speculation. These types of cases will instead require a very clear indication that the project will be realised.

Vattenfall Eldistribution AB (2020c) says that the possibilities to avoid capacity shortages in the region are good, but it depends on how Svk choose to react and act. Vattenfall Eldistribution AB (2020c) does not see any problems at a regional level with increasing the electric power demand with 2000 – 3000 MW in the region. Norrbotten is a net exporting region today and would be able to cover a lot of the demand with regional production and import the remaining demand from price area 2 which is also an export area today. However, a greatly increased power outtake in Norrbotten could lead to problems with the national power balance since the possibility of export to price area 3 and 4 would be lower.

The establishment of data centres in Sweden have not been a problem so far. This is due to that the large companies looking for establishment have made a lot of applications in several regions to find suitable locations. Vattenfall Eldistribution AB (2020c) wants to offer the opportunity of discussing locations early in an establishment process to be able to give indications of what locations should be suitable. However, this opportunity is seldom used. It is not uncommon for companies to submit applications for many locations and to hide behind shell companies or applies through organisations such as Business Sweden, which makes physical meetings difficult.

Interview with Vattenfall Eldistribution AB with focus on Stockholm

In the discussion about the future electricity demand in Region Stockholm, it is mentioned that the residential and service sector is seen as the most challenging sectors. However, studies have shown that there is little correlation between electricity demand and population growth. The reason is that energy efficiency measures are believed to compensate for the demand that arises due to new buildings and infrastructure.

Vattenfall Eldistribution AB (2020a) also mentions that there are uncertainties of what impact charging of electric vehicles will have. Requirements for electric vehicle chargers when constructing new household can result in a rapid expansion of charging infrastructure. However, the applications that are seen today are mainly for electrification of public transports. If for example, buses are to be electrified, one should think through where fast charging is necessary, and where normal charging is sufficient, in order not to increase electricity power peaks in the grid. There are two demand peaks each day, one in the morning and one in the evening, meaning that new loads want to be placed outside these times. Therefore, flexibility solutions are interesting while the grid is expanded and dimensioned for the new demand. Examples of flexibility solutions can be production, management of customers demand, and battery storage.

The situation in Vattenfall's grid is in general, ok. There are some restraints within the regional grid, but the big bottleneck is the capacity situation in the transmission. It is because the transmission grid has reached its max capacity and need to be reinforced. There are several ongoing projects planned to be finished before 2030. Vattenfall Eldistribution AB (2020a) believes that the situation will start to look better by 2023 and that the situation in the grid will be good around 2025, based on the current available information and data. However, future aspects might change, which will lead to a different assessment of the future situation. Reasons to why there is capacity restraints today is the shutdown of local production in the regional grid, large expansion of the cities, establishment of new industries, e.g. data centres in combination with long application processes for reinforcing the grid capacity.

Vattenfall says that the aim is to expand the grid in pace with the incoming applications but that it is a problem due to the time it takes to get grid concession. The concession process for both regional and transmission grids are considered too long. The long process is exacerbated by the need to restart the process when an application is rejected. This can happen if the application is deemed by Ei to be insufficient or is appealed.

The communication between grid operators in Region Stockholm is considered good, and planning meetings between the operators are held continuously. Vattenfall Eldistribution AB (2020a) thinks that customers generally have an understanding of the long application process, since they have good knowledge about the situation. Vattenfall Eldistribution AB (2020a) says that Vattenfall Eldistribution AB tries to give the customer a time perspective as quickly as possible and work with flexibility measures when possible.

Interview with Göteborg Energi about Västra Götaland

Andersson (2020) describes that changes in the industry and transport sectors are seen as most interesting when discussing how the electricity demand will develop over the coming decades. It is believed that only minor changes will occur within the residential and service sector.

Göteborg Energi has a continuous dialogue with the major industry players in their local electricity grid and is therefore also aware of the possibility that a large-scale electrification may occur. The current electricity grid is not dimensioned for the potential increase of power demand, but with good forecasts, the company believes that it will be possible to meet the future demand. To meet the challenges posed by electrification in the transport sector, Göteborg Energi wants to keep down the power peaks by promoting flexibility and prevent large-scale implementation of fast chargers during times of high load.

Andersson (2020) believes that there are relatively good conditions for meeting an increased electrification, partly because there is no acute capacity restraints today. But it is also partly because Göteborg Energi is a locally established energy company with good cooperation and transparency between both consumers and regional grid operators. Andersson (2020) points out that the issue of capacity shortage can be seen as a function of time, where an assessment of the electricity grid situation only shows a snapshot, which can change quickly. In order to maintain a good electricity grid situation, mentions two areas that Göteborg Energi want to work with:

- Maintaining grid reserve powerplants.
- Increased flexibility towards their customers.

There is also a need for increased cooperation and information exchange between grid operators in the region. The majority of the collaborations are currently linked to specific projects, but an extended collaboration on forecasting electricity demand is believed to provide better conditions for developing the grids within the region from a system perspective. Andersson also sees a need to shorten lead times for grid expansions, especially when reinforcements in the regional or transmission grids are involved. Electricity grid operators at all levels would need to be better prepared for how to respond to inquiries regarding increased power demands in order to speed up the decision-making process. Andersson describes that it is often necessary to use unofficial communication channels in order to get a quick preliminary response from the regional grid operators about whether or not there is available capacity. He also describes that he would like to see better-defined project portfolios that show what capacity is available in the short and long term and what measures are needed to realise, projects at specific connection points.

Interview with Öresundskraft with focus on Skåne

The annual electricity demand in the areas that Öresundskraft operates has been relatively constant during the last two decades. However, the peak power has increased and can be around 220 MW for the Helsingborg area during cold winter days. The power demand for Öresundskraft is also described to correlate strongly with the outdoor temperature.

Öresundskraft have gradually increased the grid capacity as part of the work with grid planning. They currently see no direct risks of capacity shortages in their grids and have good opportunities to meet an increased demand. Local electricity in two CHP-plants located in Helsingborg creates a marginal against the regional grid, giving the possibility to balance with local production at power demand peaks. However, it is mentioned that if an industry would apply for a big power demand, each case must be evaluated individually.

The planning horizon for grid expansions are described to vary depending on the type of expansion. If all permits exist, the process of upgrading the grid can be quite short, since construction is not that time-consuming. If a new concession is required, the process will usually be much longer. The permission process is therefore seen as the major bottleneck for grid expansions. For planning the local grid, the planning horizon often follows the development of the city, where grid planning, for example, may come in connection with when the municipality prepares a new local plan.

Öresundskraft AB (2020) describes that it is important to create good conditions at the system level when developing the electricity grid. A number of measures to facilitate and meet electrification are described.

- Encourage flexible use of electricity as a way of optimising the load on the grid.
- Be active and participate in networking meetings to help influence the development of the electricity market and participate in both regional and national scenario work.
- They are also having meetings with their biggest customers to explain the situation in the grid.
- Become better at guiding actors who want to establish an electricity-demanding business by providing a hint as to where there is available capacity in the grid

It is also stated that they have a good relationship with connecting regional grid operators, but that communication could be improved even more.

Interviews with Svenska kraftnät

With Svk two interviews were held. One with the focus on how Svk works with scenarios and one with the focus on the grid situation nationally and in the four investigated regions.

Interview with Svenska kraftnät with focus on scenarios

Svk is currently working with reviewing and updating their long-term scenarios. Brunge (2020) describes that the applications to Svenska kraftnät related to new demand have increased significantly in recent years. Partly as a result of national climate goals, but also because of increased interest in establishing data centres and other types of industries in Sweden. Brunge (2020) explains that the increase in demand in some cities and regions have been difficult or even impossible to foresee. The yearly demand in Sweden has been on the same level in the last decades. However, in recent years some of the application is at the same level as the demand for a medium-sized city. As a result, (Brunge, 2020) believes that the new version of Svk's long term scenario of national electricity demand will be around 200 TWh in 2045. Brunge (2020) also validates the thesis results produced from Phase 2 and says that they are generally in line with the development that Svk sees. Brunge (2020) explains that there are large uncertainties in forecasting the electricity demand, in particular the amount of data centres and the impact of energy efficiency measures. For example, Svk assumes, according to the Energy authorities' long term scenarios, that the electricity demand within the residential and service sector will decrease due to energy efficiency measures.

Brunge (2020) explains that the power system is facing major investments and that their planning horizon extends as far as their long-term scenarios. Brunge (2020) explains that Svk currently have demand related applications corresponding to over 5 000 MW up until 2026, and that electrification of this magnitude has not occurred for over 30 years. Although it is unlikely that all these applications would be realised, it does indicate the order of magnitude. The increased demand of electricity has put pressure on the grid owners to meet this demand.

Svk sees four main driving forces for investing in the grid:

- Connections of new or increased generation or consumption
- Reinvestments in current grid
- Market integration to increase or maintain the cross-border capacity between bidding zones
- System reinforcement to strengthen or maintain operational reliability.

To build and operate a new electricity transmission facility, a series of permits from various authorities are required. The application process for a concession is what Svk considers to be the major bottleneck for grid expansions and lead times of ten years are not uncommon for new transmission lines. The fact that the establishment of new demand is increasing faster than the

rate at which Svk can invest in the transmission grid is one of the reasons why the risk of capacity shortage arises.

Brunge (2020) believes that the concession application process should benefit from being structured in a better way. Better communication between Svk, as TSO, and the regional grid operators, where scenarios and forecasts are shared would allow for better planning, and this is about to be initiated. (Brunge, 2020) also believes that a greater national interest for grid infrastructure, which to a larger extent is included in the community planning, could lead to a more efficient development of the electricity system, combined with a more agile application processes and shorter lead times.

Svk makes the assessment that today there are capacity shortage in Stockholm and Malmö, but not in Luleå and Gothenburg. Brunge (2020) says that a high electrification in order to meet the climate goals, not just in Sweden but across all of Europe, in combination with shut down of local electricity production as well as nuclear means that the risk of capacity shortages will increase. Brunge (2020) gives examples of what she believes could decrease the risk of capacity shortages in the future. More cooperation and exchange of prognosis and scenarios between Svk and the regional grid owners. An enhanced "status" for the transmission grid and a more structured and clear permit process is other examples already mentioned. In addition, it is important to continue the scenario work in order to identify future system needs proactively to increase the chance to be able to meet the demand. Another much important aspect is to be able to coop with the vast change in the energy system is the development of flexible resources to be able to balance the demand and the supply for electricity and in some extent relief the grid.

Interview with Svenska kraftnät with focus on the grid situation

When discussing the current situation in the grid from a national perspective, Edfast (2020) says that there will be capacity restraints in all investigated regions by 2045 if no measures were to be taken. Therefore, Svk have projects where they are looking into the current situation and development in Sweden, making them aware of the need to increase the grid capacity in the future. For example, the NordSyd project that aims to increase the distribution capacity between price areas 2 and 3. Edfast (2020) mentions that Svk have projects that will be finished around 2030-2035. When having projects with this long time span, it is important to have a continuous discussion and follow the development in the regions about the increased electric power demand to be able to adjust the size of the project to meet the demand.

Edfast (2020) says that when assessing the grid situation and categorising it as a "traffic light", it gives a picture about the situation today but does not say anything about the ability to develop the situation in the future.

Edfast (2020) means that one of the most important factors in a successful grid development is communication. There is currently a continuous communication with the different regional grid operators, but he mentions that the communication with large industries could improve. There is also a need for industries that are interested in new establishments to establish early contact with the grid operator about their plan. E.g. data centres have short lead times for establishment compared to the establishment of a traditional industry.

Since it is expensive to expand the grid infrastructure, it is important to look at the investment from a socioeconomic perspective. Since if the grid is expanded proactively without a confirmed demand, the cost will be collective.

Edfast (2020) also mentions that flexibility will be important to be able to manage the capacity in the grid. The increased amount of wind power will require the ability to control the power demand in a smart way. One example of this is to produce hydrogen via electrolysis during low load hours and to utilise the electricity produced by the wind power.

Edfast (2020) says that Svk currently are evaluating their own organisations and are looking into what they can do to speed up their own process and how they can work proactively.

Norrbotten

The current overall grid situation in Norrbotten is good, but in the region around Luleå, the situation is starting to become strained. But this is also something that Svk are aware of, and it is part of the work on grid development. One advantage when expanding the capacity in the Norrbotten compared to urban areas is that the concession process will be smoother since there are not the same amount of people that will be affected by the new grid infrastructure.

Västra Götaland

There have been discussions about an increased electrical power demand in the region for a long time. Svk has plans to increase the capacity in the region but, Edfast (2020) are unsure about if Svk will be able to handle the possible power demand from Borealis with the current planned reinforcements.

Stockholm

There are capacity restraints in the region, but there is close communications between involved stakeholders on how to resolve it. Currently there are several projects to increase the capacity that will be finished by 2028. The plan is that this project will cover the predicted electricity power demand until at least 2035-2040.

Skåne

There are capacity restraints in Skåne and Svk are currently having a dialogue with E.ON about the development.

E.ON Interview with E.ON about the situation in Skåne

Thelin (2020) says that it is complicated to predict how the electricity sector will be in the future since the development are affected by several factors. However, electrification in the different sectors creates different challenges for the grid operator.

- Electrification of industries require good foresight in communication with the grid operator, to ensure that connection can be made within a reasonable time horizon. Both to give the grid operator time to prepare for an expansion, and to give the industry information about the time frame.
- The electricity demand from electrification of passenger vehicles are believed to develop quickly. E.ON express a worry about where the electricity demand of the chargers will appear in the local grid. The company cars are believed to be among the first to be electrified, and it is difficult for E.ON to predict where they will be charged if the users are charging at home. Electrification of heavy transports are believed to require a larger electricity power demand at certain places, but it is believed to be more predictable where the demand will appear. It is also believed to be possible to steer these demands to suitable locations.
- To be able to invest in the grid to manage expansions of cities it is important that the municipalities include the grid operators in the discussion about increasing the cities and that the include the grid infrastructure in the local plans.

The time has changed from where you could get an immediate connection to the grid, to today's situation where good foresight is needed. This is due to the fact that the grid situation in the southern parts of Skåne is strained. Communication between all stakeholders is mentioned as a key factor to be able to expand the grid in pace with the increased demand in all sectors.

During 2019 an agreement was made between the government to solve the acute capacity shortage in a short perspective. Svk will prioritise expansions in the transmission grid in the region. Due to the fact that Svk gives priority to reinforcements in the transmission grid, E.ON is aiming at enabling the expected electrification within E.ON's grid.

The reasons behind the capacity shortage in the region are shutdown of local electricity production such as Barsebräck nuclear plant and an increase in electric power demand. This has increased the need for importing electricity from other regions, but the transmission grid has not been able to expand quick enough and is, therefore, the bottleneck in solving the capacity shortages.

Concession for grid expansion is believed to be the big bottleneck for expansion of the grid and needs to be improved to shorten the lead time, e.g. by enabling different processes to be carried out in parallel. To be able to decrease the risk of capacity shortage, local electricity production, in combination with flexibility measures, are needed. E.ON currently participates in a project called

"Switch" which is a digital marketplace for flexibility with the aim of avoiding capacity shortages by optimising the use of the grid. The project has so far resulted in a flexibility of 70 MW.

Appendix C

Description of studied scenarios

Table 19: Analysis of how assumptions differ between studied national scenarios.

Climate goals	<p>The IVA scenario is the only scenario that clearly states that it is made with the assumption that Sweden will have net zero emissions or become fossil-free by 2045.</p> <p>SVK has made their forecast with the assumption that the 2050 EU goal of 80 - 95 % reduction of CO₂ emissions, compared to 1990 level, will be achieved by 2050.</p> <p>Swedenergy's scenario is made with the assumption that electricity production in Sweden will be fossil-free by 2045. However, there is no transparent description of how the targets will be reached in other sectors. The two scenarios from the Swedish Energy Agency aims at a reduction of GHG emissions but does not clearly state that the aim is to reach the 2045 climate goals.</p>
Competitiveness	<p>All scenarios predict that the Swedish industry will keep competitive. However, SVK sees a risk of increased electricity prices if solutions for demand flexibility and energy storage is not widely implemented. All scenarios believe that the industry will stay in Sweden.</p>
Economic growth	<p>Scenarios from Swedenergy and the Swedish Energy Agency (1) assumes an economic growth of 2 % per year. Both scenarios are discussing the decoupling of GDP and electricity demand. IVA is mentioning economic growth but base their forecast on current production volumes, meaning no economic growth is assumed.</p> <p>The scenario made by SVK is not transparent in if and how economic growth is taken into consideration. The Swedish Energy Agency (2) includes GDP growth but is not transparent in how it impacts the electricity demand.</p>
Energy efficiency measures	<p>The IVA scenario sees energy efficiency measures as an important factor in reaching the 2045 climate goal, and it is included in the residential and service sector. However, it is unclear if it is included in the industry sector.</p> <p>The factors that decrease the energy demand are:</p> <ul style="list-style-type: none"> - Transition from direct-acting electricity towards heat pumps - Increased efficiency of heat pumps - Energy efficiency measures such as more efficient electric motors, products and lightning <p>It is, however, unclear what impact each factor has on the electricity demand. IVA predicts that the heating demand will be the same 2045 as today.</p>

SVK assumes that energy efficiency measures and population growth will result in a net-zero change in electricity demand. Swedenergy sees energy efficiency measures as a central factor in the development of the future electricity demand and estimates an efficiency improvement of the total electricity demand corresponding to 3-4 % per year.

Swedish energy agency (1) gives an estimate of 12 TWh energy demand reduction in households due to energy efficiency measures. However, it is not stated how the electricity demand is affected by this. No prediction is made for the industry. Up until 2035, the energy demand in the residential and service sector are decreasing due to energy efficiency measures in buildings and a conversion from direct heating to heat pumps is larger than the increased demand that comes with from new buildings. After that, the energy demand will increase because of that, most of the energy efficiency measures are implemented, and the housing stock continues to increase.

Swedish energy agency (2) takes energy efficiency into consideration in the residential and service sector they assume an energy efficiency with 0.5 % per year in individual houses and second houses and 1% per year in apartment buildings. Nevertheless, nothing is mentioned about energy efficiency in the current industry.

New type of industry

The IVA base scenario is focusing on the current composition of industries and how they can convert to become fossil-free. The scenario does not include expansion of new types of industries but mentions data centres, new types of refineries and battery production as possible industries that can be established.

Swedenergy, Swedish energy agency (1) and (2) include transparent assumptions of expansion of data centres. Swedenergy predicts an increased electricity demand of 7 TWh by 2045 due to expansion of data centres, Swedish energy agency (1) predicts 8 TWh by 2050 and Swedish energy agency (2) predicts up to 5 TWh by 2030.

SVK includes expansion of data centres and the establishment of the battery industry. No information about electricity needs for these expansions are given.

Population growth

The IVA base scenario predicts that the Swedish population will grow to 11.7 million people in 2045. IVA predicts that the electricity demand for residential and service will increase from 73 TWh to 78 TWh. The factors that increases electricity demand are population growth and new consumer technology.

SVK assumes that population growth and energy efficiency measures will result in a net-zero change in electricity demand.

Swedenergy predicts a significant increase in electricity demand due to population growth corresponding to 20-25 TWh by 2045. Population is forecasted to be 11.4 million in 2030 and 12.4 million in 2050.

The Swedish Energy Agency (1) and (2) include population growth but is not transparent in what impact it has on the forecasted electricity demand.

Appendix D

Input data for estimating electrification of transports

	Norrbottnen	Västra Götaland	Stockholm	Skåne
$X_{v,r}$ Number of registered vehicles of type v in region r	Passenger Cars: 141 658 Light Trucks: 20 458 Heavy Trucks: 3 219	Passenger Cars: 789 311 Light Trucks: 85 824 Heavy Trucks: 13 884	Passenger Cars: 935 865 Light Trucks: 132 939 Heavy Trucks: 14 165	Passenger Cars: 651 510 Light Trucks: 71 651 Heavy Trucks: 119 83
$\bar{D}_{v,r}$ Average driving distance for vehicle type v in region r [km/y]	Passenger Cars: 11 590 km Light Trucks: 12 890 km Heavy Trucks: 31 780 km	Passenger Cars: 12 190 km Light Trucks: 12 590 km Heavy Trucks: 41 240 km	Passenger Cars: 12 750 km Light Trucks: 15 330 km Heavy Trucks: 33 220 km	Passenger Cars: 11 990 km Light Trucks: 14 020 km Heavy Trucks: 49 860 km
\bar{E}_v Average electricity demand for vehicle type v [kWh/km]	Passenger Cars: 0.2 kWh/km Light Trucks: 0.38 kWh/km Heavy Trucks: 2.24 kWh/km Buses: 1.29 kWh/km	Passenger Cars: 0.2 kWh/km Light Trucks: 0.38 kWh/km Heavy Trucks: 2.24 kWh/km Buses: 1.29 kWh/km	Passenger Cars: 0.2 kWh/km Light Trucks: 0.38 kWh/km Heavy Trucks: 2.24 kWh/km Buses: 1.29 kWh/km	Passenger Cars: 0.2 kWh/km Light Trucks: 0.38 kWh/km Heavy Trucks: 2.24 kWh/km Buses: 1.29 kWh/km
$n_{transport\ work,i}$ Increase in passenger or freight transport work until year i [%/y]	Passenger transport: 2020-2040: 1 %/y 2040-2045: 0.5 %/y Freight Transport: 2020-2045: 1.8 %/y	Passenger transport: 2020-2040: 1 %/y 2040-2045: 0.5 %/y Freight Transport: 2020-2045: 1.8 %/y	Passenger transport: 2020-2040: 1 %/y 2040-2045: 0.5 %/y Freight Transport: 2020-2045: 1.8 %/y	Passenger transport: 2020-2040: 1 %/y 2040-2045: 0.5 %/y Freight Transport: 2020-2045: 1.8 %/y
$A_{v,i}$ Potential share of electrification for vehicle type v in year i [%]	Passenger Cars: 2030: 30 % 2045: 85 % Light Trucks: 2030: 90 % 2045: 100 % Heavy Trucks: 2030: 3 % 2045: 35 % Buses: 2030: 90 % 2045: 100 %	Passenger Cars: 2030: 30 % 2045: 85 % Light Trucks: 2030: 90 % 2045: 100 % Heavy Trucks: 2030: 3 % 2045: 35 % Buses: 2030: 90 % 2045: 100 %	Passenger Cars: 2030: 30 % 2045: 85 % Light Trucks: 2030: 90 % 2045: 100 % Heavy Trucks: 2030: 3 % 2045: 35 % Buses: 2030: 90 % 2045: 100 %	Passenger Cars: 2030: 30 % 2045: 85 % Light Trucks: 2030: 90 % 2045: 100 % Heavy Trucks: 2030: 3 % 2045: 35 % Buses: 2030: 90 % 2045: 100 %
B_r Share of freight loaded and unloaded within region r	93 %	80 %	78 %	78 %

P_r Offered public transport in region r - buses [km/year]	17 807 492 km	116 365 907 km	121 142 049 km	75 181 297 km
Regional population 2020	250 093	1 725 881	2 377 081	1 377 827
Predicted yearly population growth in region r [%/y]	-0.2 %/y	0.6 %/y	1.1 %/y	0.9 %/y

Appendix E

Input data for estimating electricity demand in residential and service sectors

	Norrbottn	Västra Götaland	Stockholm	Skåne
$E_{r,current}$ Current electricity demand within residential and service sectors	3.00 TWh	11.82 TWh	16.32 TWh	9.11 TWh
Regional population 2020	250 093	1 725 881	2 377 081	1 377 827
Estimated change in population in region r until year i	-0.2 %/y	0.6 %/y	1.1 %/y	0.9 %/y