Co2 and Cost Impact of Pre-and Post shift of Residential Electric Loads
ABSTRACT

The Royal Seaport project, which is a project in the Clinton Climate Initiative, develops a new, sustainable city area in Stockholm and aims to reduce the greenhouse gas emissions, using pre- and post load shifting methods to reduce the peak electricity load. The Active House, that is one work package in the Royal Seaport project, is a residential building that is equipped with systems for automated demand response, such as smart appliances and electricity storage, and also local photovoltaic power and charging poles for electric vehicles.

The thesis investigates if pre- and post shifting electricity load will reduce greenhouse gas emissions and electricity cost for the residents in the Active House. The greenhouse gas emissions are investigated for three Clinton Climate Initiative cities, Stockholm, London and San Francisco to further calculate the pre- and post shifting impacts of greenhouse gas emissions and electricity cost.

A simulation tool based on statistics of the power systems is developed, to investigate the greenhouse gas emissions from electricity production and the simulator is used to solve the research questions in the thesis. The simulator calculates an hourly greenhouse gas intensity distribution during the day and the results are used to observe differences between seasons and countries. The electricity loads of the households in the Active House are also investigated to determine the peak electricity loads to be able to dimension the photovoltaic power system and electricity storage.

Some of the most important results and conclusions in the thesis are:

The relationship between the greenhouse gas emissions and the electricity production determined, in most cases the greenhouse gas intensity distribution has a similar shape as the consumption and electricity price.

The photovoltaic power system will be able to provide 30 % of the fixed building electricity load. The electricity storage could be charged during night, when the greenhouse gas intensity is low, or when the photovoltaic power system generates surplus electricity that otherwise would be given away to the utility grid.

The dimensions of the electricity storage are cycled one time during the day and calculated to be 205 kWh to be able to pre shift an electricity load of 114 kWh from the electricity peak in the afternoon. The electricity storage are able to reduce the peak power with 40 kWh/h, electricity cost with up to 137 SEK and the greenhouse gas emissions with up to 13 kg CO2 depending on season and country.

The electricity storage is not profitable in an economical point of view today, because of life time of the electricity storage and the electricity price today but mostly on the high investments cost. The cost of reducing the greenhouse gas intensity is between 8-55 SEK/ kg CO2 in average during a year, depending on season and country. The investment cost of electricity storage will be reduced in the future and in 3 years it could be profitable with electricity storage in some countries.

Further investigations about the impact of greenhouse gas emissions and electricity cost for smart appliances and electrical vehicles have also been done in this thesis.
ACKNOWLEDGMENTS

This Master thesis is a mandatory part of the degree of Master of Science in Energy engineering by Umeå University. The thesis work is done during the autumn 2010 on assignment of ABB Corporate Research in Västerås and is a part of the Stockholm Royal Seaport project, in the Active House work package.

I would like to take this chance to thank all people that have made this thesis possible, come up with ideas and helped me during this project. To start with, I would like to thank my supervisor Rickard Lindkvist for all the help and good ideas with the problem solving and developing the simulator during this thesis work. A special thank to the project leader and co-supervisor Pia Stoll, for the help with the report. I would like to thank co-supervisor Bertil Nygren of the advices and help needed to dimension the energy storage. Further I would like to thank Bengt Stridh with the help to simulate the photovoltaic power system and also thank the other members in the Active House project group. I will also like to thank my supervisor Sune Pettersson, at the Umeå University, for the opinions of the photovoltaic power system and the report. Finally I would like to thank Jan-Eric Lethagen that informed me about ABB Corporate Research and the Royal Seaport project. I would of course like to thank my family and friends that have supported me a lot during this period.

The ABB Corporate Research has been a great place to work and I have learned a lot during this thesis work.

Västerås, December 2010

Daniel Johannesson
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1 INTRODUCTION

The Royal Seaport is a new city area in Stockholm that is being built between 2009 and 2030. For this project, Stockholm city has set up a follow-up model that should ensure that the new area is sustainable developed. The area is also a part of the Clinton Climate Initiative and will use parts of the follow-up model to supply the Clinton model with data. The Royal institute of technology (KTH) has got the assignment from Stockholm city to investigate what Key Performance Indicators (KPIs) are necessary for the follow-up model. Stockholm city has also invited companies, organizations and research organizations to form research collaboration targeting sustainable development of the new city area. As a result, Fortum and ABB formed such collaboration project together with KTH to investigate how an Urban Smart Grid can contribute to sustainable development in the area. ABB, Fortum and KTH invited Ericsson, Interactive Institute, Electrolux, NCC, JM, HSB, ByggVesta and Stockholms hamnar to join them in the collaboration. One work package in this collaboration project is the Active House.

The Active House is the name of a residential building in Royal Seaport that is equipped with systems for automated demand response between a demand response service provider and its customer. The demand response service provider is typically a utility, in this case Fortum, and the customer can be the household and/or the building management.

The demand response service provider has a contract with the customer. The automated demand response system sends signals from the demand response service provider to the customer’s automated demand response system. The contract stipulates how the signals are furnished, e.g. what real-time price or load constraints the customer has for the next 24h.

The automated demand response system in the Active House will take use the demand response signals and try to shift loads to a time in the near future when it’s optimal from a GHG and cost perspective. By doing so, the automated demand response system has done a post-shift of the electricity load.

When the automated demand response system includes local electricity storage in the Active House, the storage is charged at a time point decided by the automated demand response system. This could be a time point when the GHG emissions are low or the electricity cost is low. The electricity storage is then charged before the Active House electricity loads are using the stored electricity. At the time of the electricity load request, the storage can be used instead of the grid delivered electricity. In this case, the electricity load using the stored electricity has been pre-shifted from the grid perspective.

The thesis investigates if pre- and post shifting electricity loads will reduce GHG emissions for the Active House. GHG emission from power production depends on what power plants are used for electricity production, e.g. a coal based power generation will emit more GHG than a hydro-based power generation. Load shift from one time point when fossil fuel based generation is used to a time point when hydro-based power generation is used can therefore have an impact on the total GHG emissions. At the same the load shift would have an impact on electricity cost for the electricity consumer if the electricity price was time based, i.e. a real-time electricity price.

Not all electricity loads can be shifted in time, e.g. cooking using electricity can hardly be post shifted in time, but electricity storage could possibly pre-shift this load in time.
1.1 Research Questions

The purpose of this thesis is to investigate a set of research questions related to pre- and post-shifting of electricity loads. The research questions to be investigated in this thesis are:

RQ1. How are the green house gas emissions related to the electricity production, consumption and load balance for different power systems and regional power markets?
   RQ1.1. How is the electricity production related to the hourly GHG emission for different power systems?
   RQ1.2. What is the difference between the GHG intensity between seasonal variations and between Sweden and other countries?
   RQ1.3. How does the GHG intensity depend on real-time information about the energy mix?

RQ2. How should the Active House solar photovoltaic system and the electricity storage be dimensioned to achieve the best greenhouse gas reduction and cost benefit?
   RQ2.1. How should the solar photovoltaic system be dimensioned to meet Stockholm City’s requirement on producing 30% of the building’s electricity consumption per year?
   RQ2.2. How should the electricity storage be dimensioned to obtain best possible GHG reduction and cost benefit?
   RQ2.3. What should the frequency of the local electricity storage’s charging cycle be to obtain best possible GHG emission reduction and cost-benefit?

RQ3. What impact has pre- and post shift of electricity loads in the Active House on GHG emissions?
   RQ3.1. What is the GHG impact of post shifting electricity loads?
   RQ3.2. What is the GHG impact of pre shifting electricity loads with the electricity storage?
   RQ3.3. What is the GHG impact of replacing gasoline fueled cars with electric vehicles in the Active House?
   RQ3.4. What is the GHG impact of replacing gasoline fueled vehicles with electric vehicles in an Active House in Sweden versus an Active House in another European country?

RQ4. What impact has pre- and post shift of electricity loads in the Active House on electricity cost?
   RQ4.1. What is the electricity cost impact of post shifting electricity loads?
   RQ4.2. What is the electricity cost impact per GHG intensity unit of pre shifting electricity loads using the electricity storage?
   RQ4.3. How much must the electricity price volatility increase to achieve a positive cost benefit of the electricity storage investment?
1.2 Research Method

The thesis has done a literature study of the literature related to the research questions. In the literature study focus has been put on the electricity markets and how the energy mixes are achieved. Especially interactions between regional markets in Europe and Scandinavia have been investigated. The thesis has further investigated the electricity load, production, and storage components of the Active House and how they can interact for the pre- and post shifting of electricity loads.

Using the information about energy markets and the Active House components, the thesis has then used Elforsk’s simulator [1] to find the electricity production cost and related information such as fuel emissions and utilization time of different types of power plants. The results of using the Elforsk simulator have then been incorporated in the “GHG emission and Electricity Cost Simulator” developed in this thesis. The thesis simulator was developed to investigate the GHG intensity of power systems and to investigate the effects on GHG emissions of Active House components. The simulations from the thesis simulator has then been used to draw conclusions about what impact different energy mixes has on pre- and post shifting of electricity loads.

1.3 Definitions, Acronyms, and Abbreviations

The definitions, acronyms, and abbreviations used in this document are described in Table 1.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Acronyms</th>
<th>Abbreviations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand response</td>
<td></td>
<td></td>
<td>In electricity grids, demand response (DR) is similar to dynamic demand mechanisms to manage customer consumption of electricity in response to supply conditions, for example, having electricity customers reduce their consumption at critical times or in response to market prices</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td></td>
<td></td>
<td>Efficient energy use, sometimes simply called energy efficiency, is using less energy to provide the same level of energy service¹</td>
</tr>
<tr>
<td>Energy Conservation</td>
<td></td>
<td>EV</td>
<td>Although energy conservation is often confused with energy efficiency, it is quite different. Both involve a reduction in overall energy use, but achieve that goal in different ways. Conservation involves cutting waste of energy whereas energy efficiency does not.</td>
</tr>
<tr>
<td>kW</td>
<td></td>
<td></td>
<td>The kW indicates the power used in 1000 of</td>
</tr>
</tbody>
</table>

¹ http://en.wikipedia.org/wiki/Efficient_energy_use
### Energy

| kWh | The kWh indicates the energy used in 1000 of watt hours. |

### Power

| Electric power is defined as the rate at which electrical energy is transferred by an electric circuit. The SI unit of power is the watt, [W]. |

### Nordic energy mix

| This is the mix of energy sources used to produce the electricity distributed by the distributor company and sold by the retailer. E.g. 30% hydro-generated electricity, 50% nuclear power generated electricity etc. The Nordic energy mix is varying dynamically and hence the CO2 emission of the energy mix. |

### Electricity retailer

| An electricity retailer is a company which buys electricity at wholesale prices from a power generation company and then sells this electricity to consumers, such as individual households and businesses. Consumers are able to choose which retailer they wish to buy their electricity from. |

### Electricity distributor

| The electricity distributor owns the distribution network. There are several distributors in Sweden. |

### Aggregator

| An electricity retailer could develop a business based on the demand response of commercial and industrial customers when needs in reserve capacities increase. The business is supposed to be run by an electricity supplier, called “Aggregator” who contracts a large number (from 1000 to 100,000 or more) of small to medium-sized flexible clients. |

### Time Of Use

| Time of Use contracts are set up as a certain price for a certain day’s consumption. Time Of Use contract differs from Dynamic Pricing Program. |

### Dynamic Pricing

| Predefined tariffs depending on various parameters |

### Energy Management System

| Energy Management System Logic for e.g. deciding the optimal starting time for the wash |
1.4 Thesis Outline

This report is structured as follow. The first chapter is an introduction to the thesis and its report, including the research questions and the research method. The second chapter presents the literature study of the electricity production of the Swedish power system and the electricity consumption patterns of households in residential buildings. Further literature studies of the power systems, including Sweden, United Kingdom and California, are presented in appendix, section 8. The third chapter is about the Elforsk electricity production cost simulator, which is used in the GHG simulator developed during this thesis. In chapter four, the input parameters, based on the power system literature study and the Elforsk simulator, of the GHG simulator is presented. The results of the GHG simulator and research questions are also presented in chapter four. The conclusions are stated in chapter five. The discussion of the results and the suggested future work is presented in chapter six.

Figure 1.1 presents an overview of the thesis project and how the different parts are used to solve the research questions.
2 LITERATURE STUDY

The literature study investigates electricity production and is reported on in detail in section 8. The power systems of the three cities: Stockholm, London and San Francisco, all part of the Clinton Climate Initiative, are investigated. The input data of the three power systems are used to develop a simulation model that calculates the GHG emissions from electricity production. The power system literature study provides the input data to the thesis simulator.

The literature study also investigates a number of reports discussing electricity consumption patterns of residential households and the electricity generated with renewable energy sources. The literature study also includes the electricity consumption of appliances in the households. The electricity consumption of different household appliances is studied to understand the household’s electricity consumption distribution during 24 hours of the day. The electricity consumption distribution is used to identify time points and time spans of load peaks and valleys, used to investigate the options of pre- and post load shifting.

The residential electricity consumption studies done by or done on assignment by the Swedish energy agency constitute a good source for the thesis literature study due to their detailed information, but the results vary between studies. This could depend on the different sizes and ages of the investigated residential buildings.

2.1 Electricity Production

Electricity production is studied in detail in section 8. In this section the Swedish electricity production is extracted from section 8.

The power system of Sweden is investigated to obtain a number of input data that are used in the simulator. The input data of the simulator are for instance: the installed and available electricity generation capacity, load following power, electricity consumption, exchange and price.
The Swedish electricity power grid is divided into main, region and local grids and is part of the Nordic electric grid which consists of the neighboring countries, Norway, Finland and Denmark. The Nordic grid is also connected to Russian and European grids. [2] Svenska kraftnät, SVK, is the Swedish main utility owner and provides the main grid. SVK are also responsible of the total energy balance in the system and regulates the electricity import and export if necessary. About 170 companies own different parts of the regional grid where E.ON Elnät, Fortum Distribution and Vattenfall Eldistribution are the largest utility owners in Sweden.

The electric system main actors are [3]:

- **Electric producer** owns the power plants and produces electricity. The producers reports the planned production of the following 24 hours to the balancing power authority and have a opportunity to buy or sell balance power and electric certificates.
- **Utility owner** owns the power grid and is responsible for the electricity transport between the producer and the consumer. The utility owners measure the transferred electricity between the producer and the consumer to control that the consumer gets the right amount of transferred electricity. The utility owner may not produce, buy or sell electricity according to Swedish law because of the controlling role.
- **Electric suppliers** buy electricity of the producer and sell to the consumer. The electric suppliers own sometimes the power plants and in that case are they also electric producers. The electric suppliers are able to buy or sell balance power and electric certificates.
- **Electric consumer** buys electricity from the electric suppliers.
- **Electricity market** is where the participants are able to buy or sell electricity, balance power or energy certificates.

Sweden is divided in 4 areas with different regulation power [4]. Stockholm is part of area 3 and SVK published statistics of the electricity production from energy sources and regulation power. The summary of the capacity factors, installed and available capacity and generated power for energy different sources is presented in Table 2.1 and the input data is further presented section 8.1.

**Table 2.1: The installed and available capacity of the Swedish power system.**

<table>
<thead>
<tr>
<th>Power source</th>
<th>Installed capacity [MW]</th>
<th>Capacity factor [%]</th>
<th>Available capacity [MW]</th>
<th>Generated power [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>- coal</td>
<td>2144</td>
<td>68</td>
<td>1458</td>
<td>1705</td>
</tr>
<tr>
<td>- oil</td>
<td>1354</td>
<td>68</td>
<td>921</td>
<td>1077</td>
</tr>
<tr>
<td>- gas</td>
<td>1036</td>
<td>85</td>
<td>881</td>
<td>824</td>
</tr>
<tr>
<td>- biomass</td>
<td>2625</td>
<td>51</td>
<td>1339</td>
<td>8727</td>
</tr>
<tr>
<td>- waste</td>
<td>580</td>
<td>74</td>
<td>429</td>
<td>1929</td>
</tr>
<tr>
<td>- nuclear</td>
<td>9368</td>
<td>82</td>
<td>7645</td>
<td>66969</td>
</tr>
<tr>
<td>- hydro</td>
<td>16358</td>
<td>46</td>
<td>7556</td>
<td>66188</td>
</tr>
</tbody>
</table>
The available capacity of Sweden is presented in column 3 in Table 2.1 and in Figure 2.1. Hydro and nuclear power dominates the Swedish power system. The power mix is varying during different years depending on the available amount of water in the reservoirs and affects the power production relatively much because of the large share of hydro power in Sweden. The available amount of water is varying during the year. There is a larger amount of water is available during winter and spring than during summer and autumn. These variations affect the power system by reduced or increased thermal power use.

The average power production, based on statistics from SVK [5], is used to investigate the production variations during the 24 hours in a day to be able to identify the load following power sources. Figure 2.2 presents the average power production in Sweden.
Figure 2.2: The average power production during the day. The hydro power is used as load following power.

Figure 2.2 shows that the load following power in Sweden is based on hydro power. There is no difference in load following power during the seasons, hydro power is used as load following power during the entire year [5]. The nuclear, condensing and Combined Heat and Power, CHP, power sources are running with a relatively constant power during the day. The renewable power sources produce electricity depending on the wind speed and irradiation conditions, and cannot be controlled [5].

The power has to be produced and consumed at the same time to stabilize the grid frequency. Disturbance will appear and cause power failure in some parts of the grid if the power balance is not obtained. SVK are main responsible of the power balance and in case of power deficiency the Swedish power reserve of 2000 MW is used. The power reserve consists of contracted energy suppliers and large consuming industries, which could start an extra power plant or reduce the consumption of the production to maintain the power balance.

Electricity suppliers are able to maintain the economic responsibility of the power balance themselves or contract the power balance responsibility to another electricity supplier. The responsible electricity supplier have to regulate the own production or buy energy at the electricity market to maintain the hourly energy balance in the grid. The electricity suppliers make a 24 hour consumption prognosis based on temperature, weather and the energy habits of the consumers. The consumption prognosis is reported to SVK and together with the production prognosis the SVK are able to plan the energy production and consumption for the next 24 hours. The production units and load reducing industries of the Swedish power reserve are shown in Table 2.2. The fuels of the power reserve are oil and gas.
Table 2.2: The Swedish peak load power reserve administrated by Svenska kraftnät

<table>
<thead>
<tr>
<th>Owner</th>
<th>Unit</th>
<th>Power (MW)</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maalered AB</td>
<td>Aros, block 3</td>
<td>243</td>
<td>Oil</td>
</tr>
<tr>
<td>Korsnäs AB</td>
<td></td>
<td>120</td>
<td>Oil</td>
</tr>
<tr>
<td>Karlshamn Kraft AB</td>
<td>Karlshamn, block 1</td>
<td>330</td>
<td>Oil</td>
</tr>
<tr>
<td>E.ON. Bråvalla</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sverige AB</td>
<td></td>
<td>220</td>
<td>Oil</td>
</tr>
<tr>
<td>Vattenfall AB Heat</td>
<td>Slite, Stenungsund och Visby</td>
<td>396</td>
<td>Gas and Oil</td>
</tr>
<tr>
<td>Sum production</td>
<td></td>
<td>1309</td>
<td></td>
</tr>
</tbody>
</table>

| Load reduction  |                   |             |            |
| Stora Enso AB   | 150                |             |            |
| AV Reservefeld  | 70.4               |             |            |
| Holmen AB       | 215                |             |            |
| Belesa ScanDust AB | 18.5               |             |            |
| Rotteros Bruk AB | 25                 |             |            |
| INEOS Sverige AB | 30                 |             |            |
| Copen-Engel AB  | 73.8               |             |            |
| Sum reduction   | 587.7              |             |            |
| Sum total       | 1891.7             |             |            |

The electricity consumption of the Swedish power system over 24h and during the four seasons, Figure 2.3, is obtained from SVK statistics [5].

![Electricity consumption graph](image)

Figure 2.3: Electricity consumption in Sweden over 24h for the four seasons

The electricity demand is largest during winter and is smallest during summer. This depends on the large need of heating and lighting of the houses during the winter in Sweden. The peak consumption during winter occurs in the afternoon and during the summer season the peak consumption occurs in the middle of the day.
The exchange between the neighboring countries affects the power production and GHG emissions. The exchange is investigated and included in the GHG simulation model to increase the accuracy of the results.

The Swedish electricity grid is connected to the Scandinavian power grid, Nordel, which includes neighboring countries, Norway, Denmark and Finland. The Scandinavian power grid is connected to other grids in North Europe, Baltic and Russia.

The energy mixes of electricity production in Europe and in the other countries of Scandinavia consist of other energy mixes than in Sweden. The production mixes consists in most cases of a relatively large share fossil fuels burned in condensing power plants. The large amount of fossil fueled power plants implies a large GHG emission.

The Swedish electricity power mix has a large share of renewable and nuclear power and relatively low GHG emissions. Import and export is necessary to equal out electricity surplus and deficiency between the grids.

Norway has a larger share of hydro power than Sweden and uses it as base load and load following power source.

The production mix of Finland consists of one half of renewable energy and nuclear power. The other half consists of thermal condensing power and CHP.

Denmark’s electricity generation mix consists of condensing power, CHP and wind power where half of the total production is generated by coal-fired power plants.

Germany has an energy mix of 67% fossil fuels, 20% nuclear and 13% renewable energy.

The energy mix of Poland consists mainly of fossil fuels, 93 % coal.

The hourly exchange of electricity from Sweden to the neighboring countries is published at Nordpool spot market [7]. The total monthly exchange between the neighboring countries is obtained from SVK statistics [8].

![Import (+) Export (-)](image)

Figure 2.4: The power import and export of Sweden between the years 2004-2009. A positive value is import and a negative value is export.
The exchange during the seasons is shown in Figure 2.4 and is an average of the monthly exchange between the years 2004-2009.

Sweden exports energy to Denmark, Finland, Germany and Poland during most of the year. Sweden export electricity to Norway during spring and import during the rest of the year. Sweden exports electricity to Finland during spring and summer but Sweden imports a larger amount during autumn and winter. The import from Poland during autumn is relatively small.

The exchange has to be investigated by hour to be included in GHG model. The exchange between Sweden and the neighboring countries are shown in Figure 2.5. The effects of import and export between Sweden and Norway are relative low since the power mix is similar and mainly based on hydro power.

![Figure 2.5: The hourly power total import and export between Sweden and Finland, Denmark, Germany and Poland during the seasons. Positive values are import and negative values are export of electricity.](image)

The Figure 2.5 shows the total power exchange in MWh/h, which is the average electricity exchange during one hour, between Sweden and the neighboring countries Finland, Denmark, Germany and Poland during 24 hours. The graphs are based on hourly data from Nordpool Spot during the years 2008 and 2009.

Sweden imports electricity during the night from the neighboring countries. The import during night could depend on the relatively large amount of electric heated buildings in Sweden and the low energy consumption of Germany, Poland and Denmark. The energy consumption increases during the day for these countries and import power from Sweden. Sweden has the largest exchange of power with Denmark and Norway of the three neighboring countries. The largest amount of imported electricity is during autumn and winter. The largest export is during spring and is probably depending on the hydro power and the large volumes of water in the reservoirs because of snow melting.
Sweden has hydro power as load following and regulation power source. That gives the opportunity to store hydro power and import electricity from the thermal dominated power systems when the import price is low. The stored electricity generated by hydro power could be exported when the export price is higher.

The hydropower dominance in Sweden leads to relatively stable prices during a typical day in contrast to the Continental prices with a wide variation between low demand periods and high demand and peak load periods [9].

The electric price of Sweden is available at Nordpool spot [10].

![Electricity price chart](image)

**Figure 2.6: Electricity price at the Swedish Spot Market over 24h and seasons**

The electricity price of Sweden is lower during night and higher during the day. The maximum peak price during the years 2008-2009 is about 1400 öre/kWh and the lowest electricity price could sometimes be negative, when the power system has a large surplus of electricity.

Statistics of the electricity price of the neighboring countries is available at Nordpool spot [10], EEX [11] and the Polish power exchange [12]. The electricity price in the Nordic countries is similar to the Swedish electricity price due to a common Nordic electricity market. The prices in Germany and Poland vary more than the Nordic electric price.

### 2.1.1 Electricity Production GHG emission calculation

There are different methods to investigate the GHG emissions from electricity production. To solve the issue of how the GHG emissions are related to electricity production two main methods are investigated. The methods are the *marginal production emissions* and the *yearly average emissions from an energy mix* [13]. The methods are relatively different but in this thesis the two methods are combined to obtain the results.
2.1.1.1 Marginal Production Emission Calculation

The marginal production emissions method is based on real time data of the electricity production. If real time data of electricity production divided into energy sources categories is possible obtain, the margin production method could be used. Real time data of the amount of electricity produced in each power plant type is needed in the calculations.

The GHG emissions from Life Cycle Assessment, LCA, or fuel emission are also needed to obtain the margin production emissions from electricity production. The calculations and results are possible to make as detailed as wanted if the real time data is used because of the high resolution of the data. The problem with this method is to obtain the real time data of electricity production.

2.1.1.2 Yearly Average Emission Calculation

The energy mix emissions are based on statistics of the electricity production. The total amount of electricity produced by the different power plants in an energy mix during a year is used in the calculations. The average emissions are calculated by using GHG emissions from LCA or fuel emission data for each type of power plant and energy source. The emissions are presented in an average during the year. This method is, depending on the resolution of the statistics, possible to investigate the emissions with a resolution for a year. Therefore this method is impossible to use for calculations of the daily GHG variations and thereby also the load balance.

2.1.1.3 Thesis GHG Emission Calculation Method

The method of this thesis is a mix of the two methods presented in section 2.1.1.1 and 2.1.1.2. The thesis GHG emission calculation is using the Marginal Production Emission calculation but with statistical data, e.g. installed capacity, energy consumption and exchanged electricity with neighboring countries. The GHG emission calculation method used in the thesis is therefore a version of the Marginal Production Emissions calculation method but with influences from the Yearly Average Emissions calculation method. The thesis GHG emissions calculation method would be improved with the real time data for the Swedish power system but these are as of today not available.

2.1.2 Electricity Production Life Cycle Assessment

All electricity production plants emit GHG emissions and contribute to the global warming problem. A life-cycle assessment includes the emissions during the whole life time of the power plant. For instance raw materials, constructing, transport of fuel, conversion to electricity and waste management and the emissions generated from fuel during this periods is calculated in the LCA. Weisser has published a study of the life-cycle assessment GHG emissions of fossil fuel and renewable energy systems [14]. The life-cycle assessment GHG emissions of different power sources are shortly presented below and a summary of is the emissions are shown in Figure 2.7. The emissions are presented in g CO2 equivalents per produced kWh of electricity.

The presently operating lignite power plants have emissions between 1100-1700 g CO2-eq/kWh. In the future (2020) the lignite power plants with increased efficiencies have a GHG emission just above 800 g CO2-eq/kWh.

In the operational stage of a coal-fired power plant the emissions are in the range of 800-1000 g CO2-eq/kWh, but the total emissions during life time is 950-1250 g CO2-eq/kWh. The future and advanced technologies have total emissions of 750-850 g CO2-eq/kWh.
The cumulative emissions of oil fired power plants are in the range between 500-1200 g CO2-eq/kWh.

The GHG emissions from gas-fired power plants arise during the operational phase and lie roughly between 360-575 g CO2-eq/kWh for present technologies.

The cumulative emissions of Carbon Capture and Storage, CCS technology lie in the range between 40-152 g CO2-eq/kWh and are dependent on what type of fuel burned in the power plant. Gas-fired CCS power plants have lower GHG emissions than coal-fired power plants.

Most of the GHG emissions are generated during the fuel mining and processing of a nuclear power plant and vary a lot depending on the process. The operational emissions are relatively low. The total emissions during a life time, including final storage, of a nuclear power plant are generating 2.8-24 g CO2-eq/kWh.

The emissions from photovoltaic power plants during the operational phase are negligible in comparison to the production phase. The mining and purifying process emits most GHG emissions during the PV life time and varies in the range of 43-73 g CO2-eq/kWh.

Because of the cubic relationship of the wind velocity and power output the wind power turbines have very site specific GHG emissions. The range of GHG emissions of a onshore wind turbine are 8-30 g CO2-eq/kWh, and 9-19 g CO2-eq/kWh for off-shore turbines.

The amount of GHG emissions of a hydro power plant is dependent on the size and depth of the reservoir, the climate and vegetation nearby. The emissions of a hydro power plant lie in the range of 1-34 g CO2-eq/kWh.

The GHG emissions of biomass systems lie in the range of 35-99 g CO2-eq/kWh.

![Figure 2.7: Summary of life-cycle Green House Gas emissions of renewable and fossil fueled power plants [14]](image)

Compressed air energy storage have life cycle emissions of 19 g CO2-eq/kWh, Pumped hydro storage have emissions of 36 g CO2-eq/kWh.

The LCA emission from the production of the lithium battery is studied by ELFORSK LCA comparison by Anthony Green in 2004 [15]. The LCA emissions are obtained by divide the total life cycle impact with the capacity and number of cycles during life time. Green presents a life cycle
impact of 2250.8 kg CO2-equivalents of a battery with a capacity of 90.2 kWh and 10 000 cycles which implies a LCA emission of 2.5 g CO2-equivalents/ kWh/cycle. This value is relative low compared to the variation of the GHG emissions from electricity production.

2.2 Electricity Consumption

The total energy consumption of Sweden is divided into categories [16]. The categories are presented in Figure 2.8.

![Figure 2.8: The total energy consumption of Sweden during 2008 divided into categories](image)

The total energy consumption of Sweden during 2008 was 613 TWh where the used energy in Sweden was 397 TWh [17]. The unusable energy is for example lost in nuclear power plants and due to transport- and distribution losses. The electricity consumption during the same year was 129 TWh and the largest part of electricity is used in the building and services category, about 70 TWh [17]. The remaining part of the energy consumed in the building and services category consist of for example district heating.

The industry and the transport sector are the sectors that have the largest GHG emissions in Sweden. The GHG emission from electricity and heat production is about 12% and the emissions from household energy consumption is about 7 % [18].

Since the building and service sector have a relatively high electricity consumption and the efficiency of most households products is not the best available today, the potential of electricity saving is relatively large.

2.2.1 Electricity consumption in the Active House

This section presents a summary of a number of studies of the electricity consumption in residential buildings.

The results of the studies are used to estimate the electricity consumption in the Active House households and in the building as such. The results of the studies are presented as the electricity consumption pattern during a 24 hour period. The studies are based on the residents’ behavior and their use of appliances. The electricity consumption is dependent of different parameters of the household members. The household members’ age, behavior and number are important parameters for the electricity consumption patterns of the household.
Machine specific or electricity system specific consumption is further on called a load, e.g. dishwasher load or lighting load.

### 2.2.1.1 Electricity load categories

The different electricity consumptions from the machines in the Active House are called the Active House loads and can be divided into four different categories, Table 2.3. The four categories are:

- **L_H1.** The fixed household loads, which the household members are not prepared to postpone in time, e.g. computer, TV, stove…
- **L_H2.** The controllable household loads, which the household members are prepared to postpone in time [19], e.g. the freezer’s defrost function, the washing machine, the dryer and the dishwasher
- **L_B1.** The fixed building loads, which the building management is not prepared to postpone in time, e.g. elevator, ventilation, lighting…
- **L_B2.** The controllable building loads, which the building management is prepared to postpone in time, e.g. EV charging and electricity storage charging…

<table>
<thead>
<tr>
<th>Table 2.3: Active House Load Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active House Loads</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Fixed loads</strong></td>
</tr>
<tr>
<td><strong>Controllable loads</strong></td>
</tr>
<tr>
<td><strong>Household</strong></td>
</tr>
<tr>
<td>L_H1: Computer, TV, Stove, ...</td>
</tr>
<tr>
<td>L_H2: Freezer’s defrost, washing</td>
</tr>
<tr>
<td>machine, dryer</td>
</tr>
<tr>
<td><strong>Building</strong></td>
</tr>
<tr>
<td>L_B1: Elevator, Ventilation, Lighting...</td>
</tr>
<tr>
<td>L_B2: EV charging, Electricity storage charging</td>
</tr>
</tbody>
</table>

In 2007, Kall and Widén presented a study of households’ electricity consumption in residential buildings [20]. The study investigates how much electricity is consumed by household appliances and presents the hourly electricity consumption pattern during the 24 hours. The electricity consumption patterns in this thesis are based on the results presented in the study by Kall and Widén. However, a minor change of the lighting and computer loads presented in Kall and Widén’s study has been done. The computer electricity consumption in Kall and Widén’s study is low compared to similar studies presented by Bennich [21] and Zimmermann [22]. Therefore, the computer electricity consumption in this thesis is increased to obtain similar electricity consumption as in the studies [22], [21]. The reason is that the study of Kall and Widén are based on results of the Swedish statistics bureau (SCB) from 1996 which is a relatively long time ago. Also, the lighting technology has improved since 1996, leading this thesis to assume that the households use more energy efficient lighting resulting in lower electricity consumption.
Lighting of the apartment is the largest appliance of household electricity according to ELFORSK 08:54. The second largest consumption post is the white goods, the third is entertainment appliances [23]. The efficiency of the lamps has improved and if all of the light bulbs are replaced with LEDs this category is largely reduced. Since Kall and Widén treated values from the survey by SCB in 1996 an assumption was made that half of the lamps used light bulbs of 40 W and the other half used light bulbs of 60 W. In a new house the apartments have to use low energy lamps or LED according to Swedish law. The assumed power consumption of low energy lamps or LED is 8 W. This assumption makes the values of lighting in apartments according to Kall and Widén in the same range as the total lighting consumption, if the savings is performed, according to Zimmermann.

The fixed household electricity load, \( L_{H1} \), using the thesis version of the Kall and Widén study’s results, in one residential household are presented in Figure 2.9.

**Figure 2.9:** The fixed household electricity loads of one residential household during weekdays and weekends for summer and winter

From Figure 2.9, using the definitions of fixed loads in Table 2.3, the total amount of fixed household load in one residential household, \( L_{H1} \), can be approximated to 2217 kWh/year. This is load that the energy management system in the household cannot shift in time in order to reduce GHG emissions or electricity cost.

If instead the controllable loads are considered, an impact on GHG emissions and electricity cost can be achieved by postponing the controllable loads using an energy management system in the household. By postponing the start time of the household’s controllable loads, a post-shift in time of the load is attained. If the amount of controllable household load was known, the impact
on GHG emissions and electricity cost of the post-shift of the controllable household load could be calculated. By using the thesis’ version of the Kall and Widén study the controllable loads over 24h can be calculated, Figure 2.10.

The total amount of controllable household load, \( L_{H2} \), of one residential household is according to Kall and Widén study 760 kWh/year.

The fixed and controlled household loads together are larger during the weekends than during the weekdays. There is also a difference between summer and winter seasons mainly depending on the use of lighting [22].

The building electricity loads consists of fixed building loads and controllable building loads. The charging and heating of electric vehicles are controllable building loads. The charging of building electricity storage is also a controllable building load that pre-shifts fixed building electricity load from a grid perspective. The reason is that the discharging of the electricity storage reduces the building load at the discharging time interval from the grid perspective. The building load was for that purpose increased earlier at the charging time from the grid perspective.

The assumption is that peak shaving of the electricity load curve will have a positive impact on GHG emissions and electricity cost for the Active House. This assumption will be further investigated in the second part of the literature study that takes a deeper look into how power systems work. If the building load’s peak is to be shaved, then the size of the building load and its distribution over 24h must be determined in order to know how much load can be pre- and post-shifted. The amount of building load that is pre-shifted decides the dimension of the electricity storage used to pre-shift the load. Cost and GHG emissions saved by the pre-shift are also influenced by the dimension of the electricity storage.

The fixed building load is load that the building manager is not willing to post-pone in time, e.g. ventilation system load, elevator load, laundry room appliance load and stair house lighting load.

To obtain a value of the fixed building load, two studies have been used. The first study is the study done by ATON Teknikkonsult AB on the assignment of the Swedish energy agency [24]. This study reports on the electricity consumption of the ventilation system, appliances in the laundry room and stair house lighting. The second study is done by the Swedish energy agency [25] and reports i.e. on elevator electricity consumption. The fixed building loads, presented in
Figure 2.11, are extracted from the Swedish energy agency studies [24], [25]. The fixed building loads are hourly distributed over the day by the thesis writer since no details could be found in the literature study how the fixed building loads are hourly distributed over 24h.

![Fixed residential building load](image)

**Figure 2.11: The fixed residential building loads over 24h**

There is no difference between weekday and weekends in the fixed residential building load. The example of the distribution of building load, \( L_{B1} \), presented in Figure 2.11 have a total load of 295,650 kWh/year of an Active House with 120 apartments and an area of 19,710 m\(^2\). The total amount of fixed building load varies depending on the size of and number of households in the Active House and is thereby scaled to the proper size.

### 2.2.1.2 Electric Vehicle Charging

The charging and comfort heating of the electric vehicles in the Active House are based on a number of assumptions:

- Each Active House parking spot is equipped with a charging unit for electric vehicles
- Each household has access to 0.5 parking spot, i.e. there is a waiting queue for a parking spot in the house
- Electric vehicle battery is assumed to have a capacity of 20 kWh
- The electric vehicle is charged at the driver’s work’s parking space at daytime
- When the driver arrives at the Active House and plugs in the electric vehicle in the charging unit, the state of charge, SOC, of the battery is assumed to be 50%.
- The heating of one electric vehicle is assumed to use 1 kW heating power during 1 hour
- The battery of the electric vehicle is assumed to be charged during all of the time that the electric vehicle are plugged in and the battery is assumed to be fully charged one hour before departure. The charging power is then distributed during all available charging hours during the electric vehicle are connected to the charging pole.

The arrival time and departure of the electric vehicle is assumed to be normal distributed in the afternoon and in the morning. Table 2.4 and Table 2.5 present the assumed arrival time and departure time of the electric vehicles.
Table 2.4: The arrival time and share of electric vehicles plugged in and charging.

<table>
<thead>
<tr>
<th>Arrival time</th>
<th>Share that plug in during that hour [%]</th>
<th>Total share plugged in [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>17</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2.5: The departure time and share of electric vehicles plugged in and charging.

<table>
<thead>
<tr>
<th>Departure time</th>
<th>Share that plug out during that hour [%]</th>
<th>Total share plugged in [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2.12 presents the total residential building load including the fixed residential building load, L_B1, and the controllable building load, L_B2.

**Figure 2.12: The total residential building loads over 24h**
The total amount of electricity needed to charge one electric vehicle during a year is 3741 kWh, if the electric vehicle is used every day and the heater is used every day during the winter season. These calculations are just based on assumptions because of the pre study phase in the Royal Seaport project. In the future, when the Active House is build, the building server will investigate the best charging time of the electric vehicles and distribute the load on the best way considering the GHG emissions and electricity cost.

The electricity needed to charge and discharge the energy storage is also controlled by the building’s energy management system in the future. To estimate the dimensions and then also the benefits of the electricity storage, such as reduced GHG emissions and electricity cost for the consumer, an example of how to use the building electricity storage is presented in the following section.

2.2.1.3 Building Electricity Storage

Lithium ion battery is used as electricity storage in the Active House. The lithium battery type is used because of the high specific energy capacity, but one downside is that the lithium battery is a rather new and expensive technique. The investment cost of a lithium ion battery is relatively high because of the young battery technique and is about 1000 USD/kWh today but will be lowered in 3 years to about 250 USD/kWh [26]. The battery has an assumed life time of 10 000 cycles and the life time will probably also increase in the future. The investment cost, life time and variations of the electricity price during the day are important parameters to consider, investigating the RQ4. The variations of the electricity price are determined in the Power system literature study, section 8, and are crucial to the electricity storage economical studies.

The properties of the lithium ion battery are: 1) The efficiency of the charge and discharge cycle is 93%. 2) The state of charge of the lithium battery have to be minimum 20 % and maximum 80 % otherwise the life time of the battery is reduced. This implies that the useable capacity of the battery is only 60 % of the total capacity.

2.2.1.4 Building Solar PV System

The amount of generated power from the Solar PV cells are simulated in the thesis and compared with the building electricity consumption.

The energy consumption of the building in Royal Seaport is limited to 55 kWh/m² during a year where the building electricity consumption is included and limited to 15 kWh/m² during a year [51]. The household electricity consumption is limited to 20 kWh/m² during a year [51]. The passive house concept is defined by the heating energy consumption of a passive house is limited to 30 kWh/m² during a year [27]. The Royal Seaport buildings are therefore nearly passive houses.

The Royal Seaport buildings have to install local renewable energy sources that provide 30 % of the yearly building electricity consumption.

The generation of electricity by the PV panels in the area of Stockholm are simulated with the program PVSYST v. 5.06 [28]. The results of the simulations are generation data for each hour during one year. The program calculates the hourly generation depending on a number of parameters. The input parameters and assumptions of the simulation are stated below:
Table 6 Solar PV simulation Parameters

<table>
<thead>
<tr>
<th>Solar PV generation Simulation Parameter</th>
<th>Solar PV generation Simulation Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>0° (south)</td>
</tr>
<tr>
<td>Pitch</td>
<td>45° towards the horizontal</td>
</tr>
<tr>
<td>Installation</td>
<td>Fixed, no shadowing from neighboring buildings</td>
</tr>
<tr>
<td>Module</td>
<td>Gällivare Photovoltaic 230</td>
</tr>
<tr>
<td>Efficiency</td>
<td>13.9 %</td>
</tr>
<tr>
<td>Module Power</td>
<td>139 W/m² ~ 7.2 m²/kW</td>
</tr>
<tr>
<td>Inverter</td>
<td>SMA Sunny Mini Central 10000 TL</td>
</tr>
<tr>
<td>Inverter Efficiency</td>
<td>97.7 %</td>
</tr>
<tr>
<td>Production</td>
<td>1008kWh per installed kW in average during a year</td>
</tr>
</tbody>
</table>

The average generation of the PV panels during 24 hours is based on the assumptions above and is simulated by the PVSYST program and the result is presented in Figure 2.13.

![Photovoltaic power generation](chart.png)

**Figure 2.13:** The daily power production during the seasons and year from a PV facility of 10.3 kW Gällivare Photovoltaic 230 modules

The power generation seen in Figure 2.13 is distributed in the same shape during all of the seasons. The average peak power production during spring and summer is about 2.5-3 times larger than during winter.
The hourly data of the production are scaled linear to obtain an approximately production of other sized PV installations in the Stockholm region. The PVSYST program could be used to obtain more accurate production data of different sizes of the PV installation at different locations.

Four building companies NCC, JM, HSB and ByggVesta will build one Active House each in the Royal Seaport project. The NCC Active House is the largest of the four different Active Houses which includes 120 apartments. The results of the simulations and the dimensions of the components of the NCC Active House are calculated to solve the research questions RQ2, RQ3 and RQ4 and will be presented in this report. The assumptions considering the NCC Active House are stated below:

- Number of apartments: 120
- Fixed building load: 15 W/m²/year
- Heated area of the building: 19710 m²
- Number of electric vehicles: 60
- Power of engine heater for electric vehicles: 1 kW
- Installed photovoltaic power: 99.3 kW
- Area of photovoltaic power system: 715 m²

The heated area of the building and installed photovoltaic power is based on the properties of the HSB max building and these parameters are scaled linear to obtain the proper size for the NCC Active House.

The electricity generated by the photovoltaic power system and the building load are investigated to solve the research question RQ2.1, where the production of the PV system and the fixed building load, \( L_B1 \), is determined. The PV production and fixed building load is investigated to conclude if the generated electricity could provide 30 % of the fixed building consumption and fulfill the requirements set by Stockholm city.

The PVSYST program calculates that the photovoltaic power system, installed in the NCC building, generates 100 608 kWh during a year. The total amount of fixed building electricity load during a year is 295 650 kWh. The PV panels will generate electricity that could provide 34 % of the fixed building electricity load, and by that fulfill the requirements of Stockholm city. There is a number of factors that could affect the PV electricity generation negative, such as snow and dirt. The yearly irradiance varies with ± 10% which also affects the PV generated electricity. To investigate if all of the PV generated electricity are consumed right away in the building and if a surplus of electricity occurs, the average generation of the PV panels during a year is calculated and presented in Figure 2.14.
The PV production exceeds the yearly average building consumption a short period in the middle of the day. The amount of surplus electricity that exceeds the building consumption is 17 kWh per day, about 6% of the total generated electricity. The electricity generated by the PV panels and used by the building load appliances, in this average case, are about 32% of the total building load.

The PV power system generates electricity depending on the intensity of the sun which is very dependent on the seasons. During winter the PV panels produce a small amount of electricity and during summer the electricity generation is larger. The photovoltaic peak power generation is important to investigate to determine the amount of surplus electricity and what it could be used for.

The largest peak power generation from the PV panels occurs during spring or autumn and slightly larger than power peak the summer and substantially larger than in the winter season. The maximum peak power generation during the year is compared to the building load and both are presented in Figure 2.15.

![Figure 2.14: The average photovoltaic power generation during a year and the residential building load](image)
Figure 2.15 shows that the surplus electricity generated during this peak is relatively large and is 276 kWh that day, the surplus electricity is about 47% of the total generated electricity that day.

The hourly results of the PVSYST program and the fixed building load are compared and the surplus generated electricity during a year is 28215 kWh, which corresponds to about 28% of the total generated electricity. The generated electricity is larger than the building consumption for 248 days during a year and the average electricity surplus during one of those days is 114 kWh.

The amount of surplus electricity from the PV panels could be used to charge electric vehicles in a different time than the assumed charging time presented in the Table 2.4, or to charge the electricity storage and use the electricity later. The generated electricity could also be “given away” to the utility grid but that is a secondary solution.

The amount of surplus electricity generated by the photovoltaic cells is determined when the research question RQ 2.2, about electricity storage dimensioning, is investigated. The GHG emissions from electricity production and electricity price are also important parameters to investigate to solve this research question. Further analysis is needed and the results of the research question are presented in section 4.6.

3 ELECTRICITY PRODUCTION COST SIMULATOR

To obtain the GHG emissions from electricity production a number of parameters and statistical input data have to be investigated. The available capacity determines the available electricity generation capacity that represents the width of the energy sources/power plants in Figure 3.1 and will be presented further in section 4.

The electricity market depends on supply and demand and the electricity market stakeholders will push for a low electricity price as possible. The most important parameter in the thesis simulator is the electricity production cost because it determines the start up order and which power plant
that will be used or unused. The production cost is represented by the height of the energy sources/power plants in the supply curve, seen in Figure 3.1. The energy sources/power plants are arranged in the order, where the cheapest are to the left and increasing production cost will be arranged to the right, as seen in Figure 3.1.

![Supply Curve](image)

**Figure 3.1: The electric price depends on demand and supply [29]**

The power demand, the vertical dotted line in Figure 3.1, is mostly lower than the available power and therefore the most expensive power plants are never started.

The electricity production cost is investigated in the study of “El från nya anläggningar 2007” by Elforsk [30]. The study includes a simulation model where the effects of a number of parameters could be investigated. The parameters and results of the Elforsk simulation model will be presented in this section.

The Elforsk simulator is used by electricity producers and politicians to compare the electricity production cost for different power plants and energy sources in pre studies before investments in new power production [31]. The model includes 20 different power plants of different energy sources that are suitable for the Swedish and Nordic power systems.

The input parameters of the Elforsk simulator are among others fuel prices, interest and depreciation time of the investment cost, utilization time, heat income, taxes, fees and subventions. The parameters could be modified to suit other countries than Sweden.

The political instruments such as taxes, fees and subventions affect the GHG emissions. The effects of the different political instruments in the future could be investigated to speculate about the GHG emissions from electricity production in the future.

The results of the Elforsk simulator are mainly the electricity production cost, presented in Swedish öre / kWh, of the power plants. The Elforsk simulator and report contributes with further data, in addition to the production cost of different power plants, for example the utilization time and CO2 emissions from combusted fuel used in the power plants. The electricity production cost is input to the simulation model developed in this thesis.
4 GHG EMISSION AND ELECTRICITY CONSUMPTION COST SIMULATOR

The literature study part about electricity consumption of the Active House is presented in section 2.1.2 and the literature study part about power systems is presented in the section 2.1.1. The results of the literature study are used together with the Electricity Production Cost simulator presented in section 3 to develop the GHG Emission and Electricity Consumption Cost simulator in this thesis. The GHG Emission and Electricity Consumption Cost simulator is used to answer some of the research questions from section 1.1.

The simulation model is divided into two parts: Power system and Active House. The first part investigates the GHG intensity of different power systems and tries to answer RQ1. The second part investigates the GHG emission impact and electricity cost impact of pre- and post shifting loads in the Active House. By changing the power system input parameters it is possible to investigate the affects of pre- and post shift of electricity for the Active house concept in different power systems. The second part of the simulator therefore depends on the results in the first part and answers the research questions RQ2, RQ3 and RQ4.

The GHG emission and Electricity Consumption Cost simulation model is based on a number of parameters from different sources discussed in section 2.1.

4.1 Power System Parameters

The parameters needed in the power system part of the Green House Gas Emission and Electricity Cost simulator are:

- **Production cost per kWh.** The production cost is used to arrange the electricity production units in rising production cost order in the supply curve.
  o The electricity production cost in the thesis simulator is obtained from the results of the Elforsk simulation model 07:50 [30]. The Elforsk simulator generates a great opportunity to change the input parameters to investigate the effects of for instance different taxes. The results from the Elforsk simulator 07:50 is then copied and pasted into the thesis simulator. The results from the Elforsk simulator are used because Elforsk is a reliable source with well established results.
  o The basic most important assumption for the thesis simulator is that the margin power production is determined by the production price of electricity. The market will arrange the power production so that the cheapest power plant will start first and the most expensive power plant will start last.

- **Installed capacity.** The installed capacity is used to obtain the available capacity.
  o Statistics of the installed capacity is obtained from the U.S. Energy Information Administration, EIA [32]. The EIA has well established statistics for a large number of countries. The statistics of all countries available in the EIA statistics database are included in the thesis simulator. This statistics are included to prepare for further investigation of other power systems than the already included power systems. The total amount of installed capacity divided in the different energy source categories as presented in the literature study in section 8.

- **Generated power.** The generated power is used to obtain the hourly average generation power, which implies the capacity factors of renewable energy sources and nuclear power.
  o Statistics of the generated power is obtained from EIA and the International Energy Agency, IEA [33]. Both EIA and IEA are chosen because of the reliable and well established statistics and also because of the statistics are available for a
large number of countries. The generated power is divided in the same energy source categories as the installed capacity.

- The total amount of generated nuclear and renewable power during a year is divided with the number of hours of a year to obtain the average power in MWh/h, needed to calculate the capacity factors. This leads to the power generation data of the power source is equal during all hours of the year, but in reality the production usually vary. The production usually varies a lot during the seasons and during the day for the renewable energy sources.

- **Capacity factors.** The capacity factors are used to calculate the available generation capacity.
  - The utilization time for condensing and CHP power plants are presented by Elforsk report 07:50 and statistics from EIA and IEA and by that the capacity factors could easily be derived. The capacity factors of renewable energy sources and nuclear power is derived from statistics of the generated power. The capacity factors for energy sources are presented in Table 8.1 and Table 8.2.

- **Seasonal variation and load following power sources.**
  - The seasonal variation is included in the model, at least for the countries where statistics of the seasonal variation are available, to take the difference of production capacity into account, for example hydro power.
  - The variation during the day is represented by load following function in the thesis simulator. The load following power is used to ensure that the electricity production is always equal with the consumption to ensure a stable power system. During night when the consumption is lower some of the power plants have to run on a reduced power generation or be shut down. Some of the power sources are faster to regulate than other and are suitable to use as load following power sources. It is possible to choose the load following power in the model.

- **Available capacity.** The available capacity is used to obtain the supply curve.
  - The installed capacity of the power plants is not available at all time. The planned and unplanned stops in power production for etc. maintenance will reduce the utilization time and thereby the available capacity. The available capacity is determined by the installed capacity and the capacity factors.

- **Consumption per hour.** The consumption is used to determine the supply curve, GHG emissions curve and GHG intensity curve. The consumption is affected by the export to neighboring countries from the investigated country.
  - The statistics of electricity consumption of a country is available at different electricity statistics databases or balancing authorities. The electricity consumption of Nordic countries is available at ENTSOE [34]. The resolution of the consumption data have to be per hour or better to be able to observe the daily variations. The electricity power consumption determines the power and number of power plants that are used to produce electricity.

- **Import and export of electricity to neighboring countries.** The statistics of the import and export is obtained from electricity markets of the country, for example Nordpool spot. Most countries electricity grids are connected to the neighboring countries grids and the power systems will affect each other. The electricity consumption is provided by the power generation and the import and export of electricity. The import and export between all neighboring power grids have to be investigated to increase the accuracy of the GHG model.
In the thesis simulation model, during import the amount of electricity counts as a power source with the production cost the same as the import price. The import prices are obtained by the electricity prices of the neighboring countries. The import power source will settle in the right production price in the supply curve as shown in Figure 4.1.

- **Electricity price of the country and neighboring countries.** The electricity price of the countries is needed to investigate the RQ3 about the electricity cost for the consumer.
  - The statistics of the electricity price is obtained from the electricity markets of the country, for example Nordpool spot. The electricity price of neighboring countries is important in the thesis simulator since the production price of the imported electricity will settle in the right production cost interval in the supply curve.

- **GHG emissions from neighboring countries.** The GHG emission from an average electricity production mix during a year is used as default GHG emissions values of the neighboring countries’ electricity production to investigate the affects of GHG emissions due to the import and export. Statistics of the average GHG emissions from electricity production are available in IEA statistical database [35].

- **GHG equivalents from life cycle assessment, LCA.** The LCA emissions are used to calculate the GHG emissions from each power plant simulated and presented as the GHG emissions and GHG intensity curves in the thesis simulator. The amount of generated power of each power plant type is multiplied with the LCA factor of the power plant to obtain the total GHG emissions. The LCA factors are obtained from scientific papers [14], [15], presented in section 2.1.2.

- The life cycle assessment, LCA, is used to consider the total emissions in GHG equivalents during the entire life time of the power plant [14]. The life cycle assessment involves for example mining, production, usage and recycling.

- **GHG emissions from fuel.** The real time fuel emissions that are generated by the fuel burned in the power plants is an alternative way to compare GHG emissions than the LCA approach. The amount of emissions from the burned fuel in the power plants is presented in the Elforsk 07:50 report [30].

### 4.2 Supply Curve

The supply curve is calculated by using the production cost and the available capacity data. The simulation model has multiple power plant models of each energy source. The available power presented in the supply curve is divided equal between the power plants with the same energy source and that are chosen to be included in calculations of the thesis simulator. Figure 4.1 shows and example of a supply curve.
Figure 4.1: The production cost against the power is presented in a supply curve. The import and export affects the supply curve. The amount of available capacity increases during import and the consumption increases during export.

The hydro power and nuclear power are the largest energy sources in this example. Both are cheap and are therefore used as base load. The CHP and other thermal power are more expensive and are used at the margin power.

The electricity import are included in the supply curve, the imported electricity counts as a power source and settle in the right position depending on the import price which becomes the production price. The average GHG emissions of the neighboring country become the GHG emissions of that power source. The electricity export increases the consumption of the investigated country. The import and export effects are represented in Figure 4.1.

4.3 Greenhouse Gas Emission Curve

The emissions from electricity production are included in the simulator and the emissions from different power sources are easily compared against each other. Each type of power plant emits an amount of GHG emissions. A greenhouse gas curve is possible to obtain by joining the LCA emissions or fuel emissions together with the supply curve. Figure 4.2 shows an example of the GHG emissions from electricity production, based on the supply curve and the GHG emissions.
Figure 4.2: The Green House Gas (GHG) emissions generated by electricity production. The emissions from LCA data is presented in this example.

The GHG emissions are low for hydro, wind and nuclear power. At higher power production the GHG emissions increases and varies more. The largest GHG emissions are emitted by coal fired power. The low GHG valleys between the GHG peaks are power plants that are more expensive but with low GHG emissions, such as wind power or bio power.

This GHG emission curve has to large variations to be able to draw some conclusions of the GHG emissions due to pre- and post shift of electricity. It is impossible to optimize the reduction of GHG emissions if the variations of the GHG emissions is distributed as shown in Figure 4.2, unless real time values of the electricity production is used. Real time values of the electricity production are available at Svenska kraftnät for the next 24 hours but these values are not available for the Active House and the Royal Seaport project [36].

4.4 Greenhouse Gas Intensity Curve

By integrating the GHG emissions for each amount of power another approach, average margin approach of the GHG curve are obtained. This represents the average GHG emissions in a certain amount of power and is named the GHG intensity. The GHG intensity is shown in Figure 4.3 and is calculated by the accumulated GHG emission divided with the accumulated power, for each value of the power on the x-axis. The GHG intensity is expressed in g GHG /kWh and the meaning of the GHG intensity could be explained as, each kWh of electricity generated at a certain level of GHG intensity is generating the same amount of GHG emissions without dependence on which specific power plant.

Figure 4.3: The Greenhouse gas intensity generated by electricity production. The GHG intensity is based on LCA data.

The GHG intensity of an example of a power system, are low for hydro, wind and nuclear power and starts to increase when imported, CHP and fossil condensing power sources are used. The vertical line shows the actual consumption and the GHG intensity and for this example the GHG intensity are about 20 g GHG /kWh. The GHG intensity curve has a similar shape as the supply curve.
The GHG intensity distribution during the day is obtained by calculating the GHG intensity value for each hour during a 24 hour period. The GHG intensity distribution is used to solve RQ1 and the other research questions. The results are presented in this section.

To answer RQ1, the hourly electricity consumption and the GHG intensity of the generating power plants are investigated and the results for Sweden are presented in Figure 4.4.

Figure 4.4: The GHG intensity, consumption and electricity price during the seasons of the Swedish power system

Figure 4.4 presents the GHG intensity distribution during 24 hours. The GHG intensity has a similar distribution but varied intensity, for spring, autumn and winter seasons. The largest GHG intensity for these three seasons occurs from 8 in the morning to 8 in the evening. The consumption and electricity price are similar to the GHG intensity. The GHG intensity during summer is higher during night than during day and depends on the import of electricity from neighboring countries. The GHG intensity is relatively large during spring compared to during autumn, since the electricity production in Sweden has a large share of hydro power the GHG intensity should be lower during spring because of the large amount of water surplus in the reservoirs, but this could also be explained by the exchange of electricity between the countries. Sweden exports electricity during spring, which leads to higher GHG intensity from electricity production. Sweden imports electricity during autumn, most part from Norway, where the electricity production is mainly based on hydro power.

4.5 Active House GHG emissions in three Clinton Climate Initiative cities

The Clinton climate initiative is a foundation working to reduce the environmental impact. The main goal of this initiative is to minimize the climate crisis by reducing green house gas emissions.
emissions. Cities contribute to more than two thirds of global GHG emissions [37]. The Clinton climate initiative has partnered some of the world’s largest cities to reduce their GHG emissions. The cities promote companies and scientists to develop and build energy efficient houses, waste management programs, efficient outdoor lighting and transportation to reduce the emissions and create a climate neutral city.

Figure 4.5: The cities part of the Clinton Climate Initiative [37]

Figure 4.5 shows the cities involved in the Clinton climate initiative, where London is a partner city and San Francisco and Stockholm are affiliate cities. In the thesis, the Stockholm Active House GHG emissions have been compared with hypothetical London and San Francisco Active House GHG emissions. The United Kingdom power system and London were chosen because of the similar existing GHG intensity model, Real Time Carbon, RTC [38]. The California power system and San Francisco where chosen because of a different power system, thermal dominated, and because of the large market for smart grid and Active Houses in the United States. The power system of United States and United Kingdom are mostly based on thermal power. The RTC GHG intensity model gives a possibility to compare and validate the GHG model that is developed in this thesis.

The Swedish power system is a typical hydro dominated power system and is relatively rare in the world. The results of the Swedish power system are presented in Figure 4.4 and the United Kingdom power system is presented in Figure 4.6.
The GHG intensity is similar during all the seasons. The GHG intensity increases during the morning, about 7 am, and stays at a relatively constant level until 9 pm, were it starts to decrease again. The GHG intensity is similar to the consumption distribution during the day.

The largest difference between hydro and thermal dominated power systems is the GHG intensity level. The average GHG intensity level of the Swedish power system is about 38 g GHG/kWh and the average GHG intensity level of the United Kingdom power system is about 515 g GHG/kWh. The differences between seasons are larger for the Swedish power system than for the United Kingdom power system.
The electricity production in California uses about ¾ gas fired power and the GHG intensity has a similar shape as the United Kingdom GHG intensity but with the largest difference of lower GHG intensity, about 321 g GHG/kWh in average, due to the large share of gas fired electricity generation, Figure 4.7.

The GHG intensity curve and the GHG emissions results of the simulator depends on statistics and a number of assumptions stated previously in section 2 and 4.1. The simulator is unable to consider the large deviations of the electricity production that occurs during unplanned stops that takes place in real life. This problem could be circumvented and the results of the simulator could improve further if real time values of the electricity production were used instead of historical statistics. Real time values of the electricity production are available in United Kingdom but are unavailable today in Sweden. Svenska kraftnät has the real time values of the electricity production for the Swedish power system, but can only publish it as historical values and has no real-time interface for computer systems. The conclusion of research question RQ1.3 are that the historical statistics this simulator is based on is enough to investigate the GHG intensity of different power systems but the results would be more accurate if real time values are used in the simulator.

4.6 Electricity Storage Dimensioning

The GHG intensity, electricity price, investment cost and surplus electricity generated by the photovoltaic cells have to be investigated to be able to answer research question RQ2.2, which are to the dimension of the electricity storage. The PV generated electricity is not included in the total building load balance, in other words the PV electricity does not reduce the building load, in
this electricity storage dimensioning because of the small amount of PV generated electricity during the winter.

The largest GHG emissions occur in general from midday until the afternoon when the electricity consumption and electricity price also is large, which were concluded in RQ1, that are that the GHG emissions are similar to both the electricity consumption and electricity price. The optimal time to shift electricity loads varies for different power systems but in the general case the best time occurs from 8 in the morning to 8 in the evening during all the seasons, except the special case with the Swedish power system in the summer.

The best time to shift load is now investigated and the next step to solve this research question are to determine the dimensions of the electricity storage. The electricity storage is connected and used to pre shift loads of the fixed building electricity load, PV system and the charge and heat of the electric vehicles. The total building electricity load, including the fixed building electricity load and electric vehicles, are presented in Figure 2.12. From the Figure 2.12 it is possible to locate a large electricity load peak in the afternoon, due to the large number of electric vehicles that is plugged in and charging. The peak of the building load is reduced either by the electricity storage are discharged during this time or the electric vehicle charge is delayed to a later time.

The electric vehicles electricity load are a large share, almost the same range as the fixed apartment load and fixed building load, and since the electric vehicle load counts as controllable load it is possible to shift the load to a better time and in that way reduce the peak load. In this case the electricity storage is not needed to shift the load peaks in the same extent and could be used with the main task to store the surplus electricity of the PV system. The electric vehicles will have constraints from the drivers when the electric vehicle must be charged and may not be shifted at any time. Therefore could electricity storage be used to reduce the power peaks if: 1) the number of electric vehicles is lower and 2) the electric vehicles have to be charged during certain times.

In this example of dimensioning the electricity storage the electric vehicle charging time is assumed to be fixed as in Table 2.4, and the building load distribution during the day is presented in the Figure 2.12. The peak in the afternoon is reduced to a maximum power of 71 kWh/h by using the electricity storage. The electricity storage will be charged during the night, when the electricity is cheaper, or during the day if the surplus electricity generated by the PV system is large enough to charge the electricity storage. The building load after the charge and discharge of the electricity storage is presented in Figure 4.8.
The electricity storage needs a capacity of 205 kWh to be able to shift the 114 kWh loads as presented in Figure 4.8. The shifted amount of electricity is 8% of the total building load. The total load of the Active House is reduced from about 190 kWh/h to about 150 kWh/h if the electricity storage is used. The total load could be lowered further to 140 kWh/h if the electricity consumption of the smart appliances also is shifted from the peak period.

The electricity storage could be charged with the surplus electricity generated by the PV system during the day. The PV system generates surplus electricity during 248 days during the year. The electricity storage could be charged fully during 97 days and partly charged during the remaining 151 days, according to the hourly comparison between the produced PV electricity and the building load. The PV system still generates surplus electricity during the 97 days after the electricity storage is fully charged. This amount of surplus electricity is 7871 kWh and could be sold to the utility grid or be used in the households.

The research question RQ2.2 could be summarized with that the dimensions of the electricity storage should be 205 kWh to be able to: 1) reduce the building load peak with at least 40 kWh/h and 2) to collect the surplus electricity from the PV system during 248 days. The GHG emission and the electricity price is at a relatively large level during the afternoon compared to other times during the day, and coincide with the peak of the building load, and therefore the electricity consumption during that peak is shifted to a better period. The electricity storage impacts on the GHG emissions, related to research questions RQ3 and the electricity cost for the consumer RQ4, are presented further down in the thesis.

The research question RQ2.3, about the cycle frequency of the electricity storage during a day, depends on the investment cost and LCA emissions of the lithium ion battery and the GHG intensity and electricity price of the power system. The electricity price and GHG intensity are specific for each country and each season, therefore an individual investigation of the cycle frequency for each country has to be done. In this thesis, the three power systems of Sweden, United Kingdom and California have been investigated but the result of the cycle frequency
investigation is only presented for the Swedish power system because the results are relatively similar between the power systems.

The lithium ion battery used in the Active Houses in Royal Seaport have a life time of 10,000 cycles which corresponds to about 27 years if the battery is cycled on time during the day, almost 14 years for two cycles during the day.

The cycle cost of the electricity storage is calculated by the investment cost and the life time and is compared with the electricity price to investigate if the electricity storage is profitable. The cycle cost according to the properties, constrains and investment cost of the battery are: 1) 70 Swedish öre / kWh/ cycle if the investment cost are 1000 USD/kWh as it is today and 2) 18 öre / kWh /cycle if the investment cost are reduced to 250 USD/kWh in 3 years [26].

The cycle cost of the electricity storage has to be lower than the daily price variations, the difference between max and min of the electricity price, to be able to make economical profit. The cycle cost are 70 öre / kWh/ cycle today and is relatively high compared to the price variations of the Swedish electricity price, which are about 24 öre / kWh in average during the years 2008 to October 2010. As large price variation as possible has to be used to achieve a low economic loss as possible, which implies that one cycle per day is the best alternative today. If the investment cost of the lithium battery reduces to 250 USD/kWh which implies a cycle cost of 18 öre/ kWh /cycle the electricity storage would be profitable in average during a year. The price variations during the different seasons in a year vary and affect the electricity storage profitable calculations. The electricity price variations are presented in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1: The variations of electricity price variations of the Swedish spot price</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (2008-2010)</td>
<td>36</td>
<td>18</td>
<td>26</td>
<td>16</td>
</tr>
</tbody>
</table>

The electricity storage is, with an investment cost of 250 USD/kWh, profitable for all seasons except during autumn. The values in Table 4.1 are the electricity max price minus the min price, which shows the potential of reducing the electricity cost by the electricity storage, but the max and min electricity prices will not necessarily coincide with the shifted load. The electricity cost reduction for the consumer by pre shifting building load and the relations with the GHG emissions will be investigate in research question RQ4.2 in section 4.8.

The Swedish electricity price and variations are relatively low since the Swedish power system is hydro dominated compared to thermal dominated power systems, such as the power system of United Kingdom. If the Swedish electricity price variations increase or the electricity price variations of United Kingdom, that are about 140 öre/kWh, are investigated the battery could be profitable with two cycles in one day, as long as the cycle cost is lower than the price variations. The price variations have then to be investigated to locate the best shift time.

The GHG emissions for each cycle, depending on LCA emissions and life time, are compared with the GHG emissions generated from electricity production, to investigate if the electricity storage is profitable in a GHG perspective. The LCA emissions from the lithium battery are relatively low, about 2.5 g CO2-equivalents /kWh, compared to the GHG emissions from electricity production and could therefore be neglected. The largest difference of the GHG emissions, previously shown in Figure 4.4 and Figure 4.6, for electricity production is between
night and day and the fluctuation of GHG intensity is relatively small during the high and low emitting periods. Due to the unnoticeable fluctuations of the GHG intensity, it is in most cases no further GHG reduction by cycle the electricity storage more than one time. The largest GHG intensity reduction is done if the loads are shifted from day to night. Therefore it is better to cycle the battery one time during the day.

The conclusion of research question RQ2.3 is that the electricity storage should be cycled one time during the day because of the economic loss due to the high investment cost today. From the GHG perspective it is also good to cycle one time during the day, because there is no further GHG intensity reduction benefit with more cycles during one day. In the future when the investment cost has decreased or the electricity variations increased it could be profitable with two cycles.

4.7 Impact of greenhouse gas emissions

The GHG intensity and the controllable electricity load of the smart appliances, L_H2, are investigated to solve research question RQ3.1, which are to investigate the GHG impact of post shifting electricity loads with smart appliances. The smart appliance load shifting will be shifted to the best time by the building server, concerning the GHG intensity, electricity price and constrains set by the residents. The results of the research question presented in this section are one example of how the smart appliance electricity loads could be post shifted, since the load shifting will be different each time.

The total resident building electricity load, including the charge and discharge of the electricity storage, is investigated to be able to identify the peak load period. The smart appliances loads during this period, from 5 pm to 11 pm, are assumed to be shifted to a later time, from 12 pm to 06 am, when the GHG intensity and electricity price is lower. The amount of shifted electricity loads for one household, with these assumptions, are 1,04 kWh during one day. The hourly GHG intensity of the power systems of three Clinton climate initiative cities is presented in Figure 4.4, Figure 4.6 and Figure 4.7 and is used to investigate GHG impact by the post load shifting of the smart appliances during the certain times the smart appliances are used.

Table 4.2: Greenhouse gas reduction by shifting 1,04 kWh of the smart appliance electricity load. [ g CO2 / household / day ]

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>58</td>
<td>35</td>
<td>-6</td>
<td>9</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>68</td>
<td>105</td>
<td>118</td>
<td>130</td>
</tr>
<tr>
<td>California</td>
<td>79</td>
<td>62</td>
<td>72</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 4.2 shows that the GHG emissions are negative for Sweden during the summer, which means that the GHG emissions increase due to the post shifting of electricity loads, but the building server will consider the GHG intensity and if it is possible, shift the loads to a better time. It is possible to post shift the smart appliance loads and reduce the GHG intensity by up to 130 g CO2 for the load of 1,04 kWh, depending on the season and power system.

The research question RQ3.2, the GHG impact by the use of electricity storage, could be calculated in the same way. According to the assumptions stated in section 2.2.1.3, the amount of shifted electricity in the electricity storage, discharge 114 kWh and charge 123 kWh, is used to
calculate the GHG impact by electricity storage. The GHG impact by electricity storage results for the three CCI cities are presented in Table 4.3.

**Table 4.3: Greenhouse gas reduction by the electricity storage, charge 123 kWh and discharge 114 kWh electricity load. [ kg CO2 / cycle ]**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>7,2</td>
<td>4,0</td>
<td>-0,8</td>
<td>1,2</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>4,0</td>
<td>9,4</td>
<td>11,8</td>
<td>13,0</td>
</tr>
<tr>
<td>California</td>
<td>7,6</td>
<td>4,7</td>
<td>6,1</td>
<td>7,9</td>
</tr>
</tbody>
</table>

The frequency of number of cycles is investigated to solve RQ2.3 and the conclusion is stated previously in this section, that one cycle per day is the best option. Therefore the electricity storage is able to pre shift building loads to reduce the GHG emissions by 13 kg CO2 per day, depending on the season and power system.

The greenhouse gas impact from the charging and use of electricity vehicles, research question RQ3.3, is investigated and compared to the CO2 emissions from an average gasoline and diesel car for the three power systems.

In a Elforsk study, the electricity consumption of an electric vehicle is assumed 0,15 kWh/km, which leads to a power outtake from the utility grid of 0,176 kWh/km, considering the efficiency of the battery [39]. The same assumption is done in this thesis.

The greenhouse gas emissions generated from the electricity production to charge the electric vehicle, concerning the previously stated assumptions of charging time and battery capacity, section 2.2.1.2, is multiplied with the electricity needed to drive one km [39], to obtain the GHG emissions per km for an electric vehicle. Table 4.4 presents the GHG emissions per km for the electric vehicles in the Active House for the three CCI cities.

**Table 4.4: Greenhouse gas emissions from the production of electricity used to charge the electric vehicle, per km driven electric vehicle. [ kg CO2 / km ]**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>0,013</td>
<td>0,006</td>
<td>0,002</td>
<td>0,002</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>0,099</td>
<td>0,087</td>
<td>0,078</td>
<td>0,086</td>
</tr>
<tr>
<td>California</td>
<td>0,053</td>
<td>0,053</td>
<td>0,060</td>
<td>0,055</td>
</tr>
</tbody>
</table>

The CO2 emissions from fossil fueled, gasoline and diesel, cars for different driving lengths are also presented in the Elforsk study [39], and the summarized results are presented in Table 4.5.
Table 4.5: CO2 emissions from average gasoline and diesel driven cars in 2009 and assumed in 2014 [39]

<table>
<thead>
<tr>
<th>Drive length</th>
<th>CO2 emission [kg CO2]</th>
<th>Average CO2 emission per km [kg CO2 / km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 km</td>
<td>0.89</td>
<td>1.74</td>
</tr>
<tr>
<td>10 km</td>
<td>0.89</td>
<td>1.74</td>
</tr>
<tr>
<td>50 km</td>
<td>0.89</td>
<td>1.74</td>
</tr>
</tbody>
</table>

The average CO2 emission per km of the vehicles is calculated to be able to compare the emissions from the fossil fueled vehicles with the emissions from the electricity used electric vehicles.

The average CO2 emissions from the gasoline and diesel cars of the year 2014, presented in Table 4.5, and the GHG emissions from the electricity production, presented in Table 4.4, are used in the comparison between cars and electric vehicles. The CO2 emissions and GHG emissions could be compared since the GHG emissions are calculated in CO2 equivalents, which is the same as CO2 emissions.

From the comparisons between the results in the tables it is possible to identify a difference of greenhouse gas emissions between fossil fueled cars and electric vehicles. The differences in Sweden is large and the reduction of CO2 emissions is about 121 - 135 g CO2 / driven km, depending on the season and the type of replaced car, which is about 1 % – 12 % of CO2 emissions compared to the fossil fueled cars.

The CO2 emissions reduced by using electric vehicles in United Kingdom and California are lower than in Sweden but it is still profitable from a GHG perspective to use electric vehicles instead of fossil fueled cars. If an electric vehicle is replacing a fossil fueled car in United Kingdom the CO2 emissions will be lowered by about 26 % – 43 %, depending on the season and the type of replaced car. The CO2 emissions in California will be lowered by about 54 – 61 %, depending on the season and the type of replaced car.

Average driving length in Stockholm County is 16210 km the year 2007 [40]. If the electric vehicle is driven the same length during a year the CO2 emissions will in the best case, be reduced by 2188 kg/year.

4.8 Impact of electricity cost for the consumer

The electricity cost reduction generated by the pre- and post shifting depends on: 1) variations of the electricity price and 2) CO2 emission fee pay by the electricity supplier. The CO2 emissions fee is assumed to be 200 SEK/ton which results in an economic income due to reduced GHG emissions. The economic income due to reduced GHG emissions is relatively low compared to the electricity price variations during the day. The calculations to solve research question RQ4.1
and RQ4.2 include the income generated due to the reduced GHG emissions, even though the supplier benefit the income and not the consumer.

The post shifting by smart appliances affects the electricity cost for the consumer in the Active House and to solve research question RQ4.1 the electric price, load distribution and GHG emissions are investigated. The post shift generated by the smart appliances is based on the same assumptions as used to solve research question RQ3.1, presented in section 2.2.

The reduction of the electricity cost for the consumer by the post shifting smart appliances for the three CCI cities are presented in Table 4.6.

**Table 4.6: Electricity cost reduction by shifting 1,04 kWh of the smart appliances electricity load [ öre / household / day ]**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>9</td>
<td>8</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>75</td>
<td>23</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>California</td>
<td>20</td>
<td>16</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>

The electricity cost reduction is relatively similar for Sweden and California during the different seasons compared to the electricity cost reduction of United Kingdom. It is possible to post shift the smart appliance loads and reduce electricity cost by up to 75 öre/household per day for the load of 1,04 kWh, depending on the season and power system.

The electricity cost reduction utilizing the lithium battery as electricity storage is calculated with the properties and assumptions presented in section 2.2.1.3. The investment cost of the electricity storage, the amount of reduced electricity cost for the consumer and reduced GHG emissions from electricity production is used to solve research question RQ4.2, which is to calculate the profit of the electricity storage per reduced GHG emission unit. Table 4.7 presents the electricity cost reduction utilizing electricity storage, charged with 123 kWh and discharge with 114 kWh electricity.

**Table 4.7: Electricity cost reduction by the electricity storage, charge 123 kWh and discharge 114 kWh electricity load. [ SEK / cycle ]**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>13</td>
<td>6</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>137</td>
<td>24</td>
<td>21</td>
<td>42</td>
</tr>
<tr>
<td>California</td>
<td>23</td>
<td>8</td>
<td>17</td>
<td>21</td>
</tr>
</tbody>
</table>

The largest electricity cost reduction is during winter in United Kingdom it is possible to save 137 SEK per day during that season.

The investment and cycle cost of the 205 kWh electricity storage that is used in the other calculations, considered today and about 3 years, with an exchange course of 7 SEK/USD and a life time of 10 000 cycles are calculated and presented in Table 4.8.
Table 4.8: The investment cost and cycle cost of the 205 kWh electricity storage for the investment cost today and in 3 years.

<table>
<thead>
<tr>
<th></th>
<th>Today (1000 USD/kWh)</th>
<th>in 3 years (250 USD/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost</td>
<td>1 435 698 SEK</td>
<td>358 924 SEK</td>
</tr>
<tr>
<td>Cycle cost</td>
<td>144 SEK/cycle</td>
<td>36 SEK/cycle</td>
</tr>
</tbody>
</table>

The economic profit generated by the electricity storage is determined by the economic income, Table 4.7, which is subtracted by the investment cost of the electricity storage, Table 4.8. The economic profit is divided with the amount of reduced GHG emissions to obtain the relation between electricity cost and GHG reduction. The relations between the income, investment cost and GHG reduction is presented in equation 1, where, \( i \), is the economic profit per reduced GHG emission.

\[
i = \frac{\text{Economic income} - \text{Investment cost}}{\text{GHG emission reduction}}
\]  

The calculated economic profit per reduced GHG intensity for the three power systems for an investment cost of 1000 USD/kWh are presented in Figure 4.9.

![Figure 4.9: The profit per reduced Green House Gas intensity for the three Clinton Climate Initiative cities and the seasons, for an investment cost of 1000 USD/kWh for the electricity storage](image)

Figure 4.9 presents the profit per reduced GHG emissions during the seasons for the three power systems, but the profit per reduced GHG emission for Sweden during summer is excluded because of the increase of GHG emissions during the summer causes misleading values. The profit per reduced GHG emission is negative for all countries and seasons and therefore it is an economic cost to reduce the GHG emissions. United Kingdom has the lowest cost per reduced GHG emission during all seasons and the largest cost of reducing is during the autumn in
Sweden. The average profit per reduced GHG emission is -55 SEK/kg CO2 in Sweden, -8 SEK/kg CO2 in United Kingdom and -20 SEK/kg CO2 in California.

The calculated economic profit per reduced GHG intensity for the three power systems in 3 years, if the investment cost is lowered to 250 USD/kWh, is presented in Figure 4.10.

![Figure 4.10: The profit per reduced Green House Gas intensity for the three Clinton Climate Initiative cities and the seasons, for an investment cost of 250 USD/kWh for the electricity storage](image)

Figure 4.10 presents the profit per reduced GHG emissions during the seasons for the three power systems, but the profit per reduced GHG emission for Sweden during summer is excluded because of the increase of GHG emissions during the summer causes misleading values. For the power system of United Kingdom it is profitable to reduce the GHG emissions during the winter and autumn. The average profit per reduced GHG emission in 3 years is -11 SEK/kg CO2 in Sweden, 6 SEK/kg CO2 in United Kingdom and -3 SEK/kg CO2 in California.

The electricity cost increase and volatility is another way of investigate if the electricity storage is profitable. The electricity price and volatility will probably also increase during the 3 years before the Active House is build. The electricity volatility could be explained by how much the electricity price variations have to increase to make an economical profit of the electricity storage. The electricity price and its variations are difficult to predict because it depends on a lot of parameters. The research question RQ4.3 is solved by investigates the increase of electricity volatility needed to reach the economical break even for the electricity storage with the reduced investment cost of 250 USD/kWh. The electricity storage is utilized as the assumptions stated previously in section 2.2.1.3. The number of times the electricity cost volatility has to increase is stated in Table 4.9.
Table 4.9: The increase of electricity cost volatility to achieve economical break even before the end of the life time of the electricity storage

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>3.1</td>
<td>7.0</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>0.3</td>
<td>1.6</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>California</td>
<td>1.6</td>
<td>4.7</td>
<td>2.2</td>
<td>1.8</td>
</tr>
</tbody>
</table>

If the electricity volatility double it would be profitable with electricity storage during all seasons in United Kingdom and during autumn and winter in California but still not profitable in Sweden. The electricity volatility has to increase up to 7 times to make it economic profitable during all seasons in Sweden. With these assumptions it is already profitable for autumn and winter in United Kingdom and therefore the electricity volatility are be decreased, lower than 1 during these seasons to achieve economic break even, shown in Table 4.9.

5 CONCLUSIONS

The conclusions for the research questions formulated in section 1.1 are:

- The greenhouse gas simulator is created to investigate the hourly GHG intensity distribution from electricity production, during the day and for different power systems. The GHG intensity for three CCI cities is investigated and compared between the seasons and countries. The GHG intensity distribution during the day proves to be similar to the distribution of consumed electricity in the power system. The electricity price is also dependent on the consumed electricity and therefore the electricity price is also similar to the GHG intensity distribution.

- The GHG intensity during winter, spring and autumn in the Swedish power system have high GHG intensity during the day but varies in intensity. The largest intensities are during winter and spring. The GHG intensity during the summer season is different to the other seasons and has high GHG intensity during the night.

- The GHG intensity for United Kingdom and California are also similar to the electricity consumption and price during all seasons. The GHG intensity distribution is large during the day for both power systems. The main difference is that the GHG intensity is higher than the power system of Sweden that depends on larger use of fossil fueled energy sources in the electricity production.

- The GHG simulator developed during this thesis is based on historical statistics. The conclusion of research question RQ1.3 is that it is able to investigate the GHG intensity of different power systems with historical statistics but the results would be more accurate if real time values are used in the simulator. The real time values of the electricity production are available in United Kingdom but are unavailable in Sweden today. Svenska kraftnät has the real time information, but can only publish it as historical values and has no real-time interface for computer systems.
RQ2. How should the Active House solar photovoltaic system and the electricity storage be dimensioned to achieve the best greenhouse gas reduction and cost benefit?

- The photovoltaic power system will be able to provide 30% of the fixed building consumption and fulfill the requirement from Stockholm city. There will also be a surplus of electricity during the middle of the day that needs to be consumed by the electric vehicle charge or the electricity storage in the Active House, otherwise the electricity is given away to the utility grid. An alternative could also be that the surplus electricity is used to the household electricity consumption, if the problem to fairly distribute the PV generated electricity between the apartments, could be solved.

- In the thesis the dimensions of the electricity storage is determined to be 205 kWh. Electricity storage of this size is able to: 1) reduce the building load peak with at least 40 kWh/h and 2) to collect the surplus electricity from the PV system during 248 days. The largest GHG intensity and electricity price coincident relatively well with the building electricity load peak, during the afternoon, and therefore the electricity load during that peak is shifted to a better period by the electricity storage.

- The number of cycles of the electricity storage during the day is determined by the cycle cost, the electricity price and the GHG intensity during the day. The electricity storage should be cycled one time during the day because it is not profitable today due to the large investment cost to cycle the lithium battery. In the future when the investment cost has decreased or the electricity variations increased it could be profitable with two cycles in an economic point of view.

- From the GHG perspective it is also good to cycle the electricity storage one time during the day, because there is no further GHG intensity reduction benefit with two cycles due to the unnoticeable fluctuations in the high and low GHG intensity periods.

RQ3. What impact has pre- and post shift of electricity loads in the Active House on GHG emissions?

- The post shift of electricity loads by smart appliances has a positive GHG intensity impact. The GHG intensity could be reduced up to 130 g CO2 for the 1,04 kWh shifted electricity loads by smart appliances depending on the seasons and county.

- The pre shift of electricity loads by the electricity storage has a positive GHG intensity impact. The GHG reduction of the electricity storage of charge 123 kWh and discharge 114 kWh electricity is reduced up to 13 kg CO2 depending on the seasons and country.

- The GHG intensity is relatively low in Sweden and therefore the potential of reducing the CO2 emissions with electric vehicles is relatively large. The reduction of CO2 emissions in Sweden is about 121 - 135 g CO2 / km, depending on the season and the type of replaced car. The electric vehicle GHG emission is about 1% – 12% of the CO2 emissions from fossil fueled cars.

- The GHG intensity in United Kingdom and California is larger than in Sweden and therefore the reduction of CO2 emissions is lower. The use of electric vehicles still reduces the CO2 emissions if the fossil fueled cars are replaced. If an electric vehicle is replacing a fossil fueled car in United Kingdom the CO2 emissions will be lowered about 26% – 43%, depending on the season and the type of replaced car. The CO2 emissions in California will be lowered by about 54 – 61%, depending on the season and the type of replaced car.
RQ4. What impact has pre- and post shift of electricity loads in the Active House on electricity cost?

- The post shift of electricity loads by smart appliances has a positive electricity cost impact for the consumer. The electricity cost could be reduced up to 0.75 SEK for the 1.04 kWh shifted electricity loads by smart appliances depending on the seasons and county.
- The energy storage is not profitable in an economical point of view because of the investments cost, life time of the energy storage and the electricity price today. The profit of reducing GHG intensity, in average during a year, is therefore not positive today and it would cost 8-55 SEK to reduce 1 kg GHG emission, depending on country. In 3 years, when the investment cost has decreased the cost of reducing GHG intensity is lower, about 3-11 SEK/kg CO2 for California and Sweden. In United Kingdom during autumn and winter it is profitable in 3 years with electricity storage and the average profit of reducing GHG intensity is 6 SEK/kg CO2 during a year.
- If the electricity volatility double it would be profitable with electricity storage during all seasons in United Kingdom and during autumn and winter in California but still not profitable in Sweden. The electricity volatility needs to increase further or the other parameters, investment cost or life time, needs to improve more before the electricity storage is profitable in Sweden.

6 DISCUSSION AND FUTURE OUTLOOK

The greenhouse gas simulation model is based on historical statistical data. The accuracy of the simulator model is acceptable but could be further increased by using real time data instead of historical data. The simulator needs in that case the planned real time power system data for the next 24 hours, based on the supply and demand in the Nordpool electricity market, for the power system of Sweden to be able to calculate the GHG intensity during the next day. The real time data is available at Svenska kraftnät but is unavailable for outsider stakeholders since Svenska kraftnät has no real-time interface for computer systems. If Svenska kraftnät develop such a real-time interface the real time data could be provided to the building server in the Active House, which the building server for the appliances in the building and households could use to optimize the reduction of GHG emissions.

The building server could also be able to receive a kind of weather forecast or a solar irradiation prognosis to be able to calculate the generated electricity from the photovoltaic cells. If the building server has the information about the amount of generated electricity it could investigate if the electricity storage should be charged during night from the grid or during day by the PV system.

The Royal Seaport is build in the middle of Stockholm where it is not suitable with wind power turbines. Wind power turbines are an alternative or complement to PV power for local renewable production since the wind power generation during the day is distributed more equal during the whole day and is relatively similar as the electricity consumption. The PV generates the most electricity during the day when the electricity consumption is the lowest during the day. The surplus electricity then has to be utilized in for example electricity storage but with wind power the electricity generation is distributed more equal during the day and therefore electricity storage is not needed for this function.

The residential building electricity consumption distribution is not established by any study and is only based on assumptions. The building load could therefore be distributed different and affects the size of the electricity peaks that determine the dimensions of the electricity storage. If the
building load distribution is further investigated the dimensions of the electricity and results could be more accurate.

The electricity storage is dimensioned to be able to reduce the building peak load mainly caused by the electric vehicle charge and ventilation in the afternoon. In the first years if the number of electric vehicles less than the number of chargers the peak caused by the ventilation is shifted instead by the electricity storage.

The electricity storage is also dimensioned to be able to utilize the electricity surplus generated by the PV system, during 248 days. The electricity storage is charged with 123 kWh of the surplus generated electricity and the electricity storage will be fully charged during 97 days, if the SOC limitations are considered. It is preferable to not violate the SOC limits because it will result in reduced life time of the electricity storage. For occasional charging cycles it could be possible to charge 176 kWh of the surplus generated electricity to utilize the PV generated electricity but with the results of reduced life time. The electricity storage is assumed to last for 10 000 cycles, about 27 years, which is longer than the life time of for instance the PV system. The electricity storage could therefore, for occasional times, be charged up to 176 kWh to utilize the PV system further, but with reduced life time.

The statistics of the United Kingdom electricity price is based on a low number of values, which results in larger electricity price variations. In Figure 8.12 is it possible to observe the large variations of the electricity price during the winter. This could affect the results in research questions RQ2 and RQ4 by for example to large profit per reduced GHG intensity and by the electricity cost volatility needs to be lower. If number of values of the statistics of the United Kingdom electricity price is increased the results will be more reliable.

The maximum electricity peak could be reduced by the pre- and post shifting appliances. For a large number of buildings the reduction of peak consumption result in lower peak demand and fewer peak production power plants for the electricity producers and use of smaller dimensions of the utility grid components etc. This benefits the electricity suppliers and net owners and will probably result in lower electricity price for the electricity consumer. The relation of reduced peak power and the economic benefit for the consumer should also be considered and included in the electricity cost calculations, when the economic benefit of reducing peak power is decided.

The electricity price volatility is based on the average electricity price, which results in lower volatility during the day. If the electric price is studied for each day the electricity price volatility would be larger, resulting in a faster payback time. If the building server is able to optimize the pre and post shifting to coincide with the max and min electricity price during the day, Table 4.1, the electricity storage would also achieve the payback time faster.
7 REFERENCES


[27] Energridägivningen, Passiv- och lågenergihus. Available at: http://www.energridagivningen.se/index.php?option=com_content&task=view&id=132&Itemid=150 2010-09-10

[28] PV SYST. Available at: http://www.pvsyst.com/5.2/index.php 2010-12-09


[31] Phone call with Lars Wrangensten, ELFORSK, El- och värmeproduktion. 2010-11-18


[33] International energy agency. Available at:
http://www.iea.org/stats/prodresult.asp?PRODUCT=Electricity/Heat 2010-12-09

[34] European network of transmission system operators for electricity. Available at:
https://www.entsoe.eu/resources/publications/former-associations/nordel/annual-report/ 2010-12-09

[35] International energy agency. Available at:
http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2143 2010-12-09

[36] Phone call with Johan Svensson, Svenska kraftnät 2010-09-02


[38] Real time carbon. Available at: www.realtimecarbon.org 2010-12-09


[40] Statistiska centralbyrån. Available at:
www.scb.se/Statistik/TK_/dokument/ntal1_4_2008.xls

[41] Available at: www.jcmiras.net 2010-12-09

[42] Ocean energy council. Available at:

[43] The new electricity trading arrangements, balancing mechanism system. Available at:
http://www.bmreports.com/bwh_indo.htm 2010-11-24


[45] The new electricity trading arrangements, balancing mechanism system. Available at:
http://www.bmreports.com/bsp/bsp_home.htm 2010-10-29

[46] Singel electricity market operator. Available at: http://www.sem-o.com/Pages/MDB_SMP_EA_EUR.aspx 2010-10-29


[49] California ISO. Available at:
http://oasis.caiso.com/mrtu-oasis/home.jsp?doframe=true&serverurl=http%3a%2f%2farptp10%2f&oa%2ecaiso%2ecom%3a8000&volume=OASIS 2010-10-29

[50] Southwest power pool. Available at:

8 APPENDIX A “LITERATURE STUDY OF ELECTRICITY PRODUCTION”

8.1 Electricity Production

The electric suppliers buy electricity from the producers at the electricity market. All participators report their consumption or production per hour to the main responsible of the power balance that calculate the surplus or deficiency of electricity for the next 24 hours. The power system has to import or export electricity to maintain the power balance in the grid.

The power consumption of all households and industries varies during the day. Depending on for instance the climate of the country, there is a peak demand during the afternoon or evening in most countries. The power need to be generated and consumed at the same time and the peak demand periods dimension the power plants. The peak demand power has to be provided even if it is just a short time during the day. A lower power production during the rest of the day is possible but the efficiency of the power plant is reduced if the production is lower than the rated power. The total amount of power plants could be reduced if the demand peaks is shifted to the low demand periods during the day. This implies a more equal power generation and a higher efficiency of the system since the power plants is able to produce at the rated power.

The power balance is controlled by the frequency in the grid and it is stable when the production is at the same level as the consumption. The extra power used to maintain the frequency during normal conditions consists of load following power and regulation power.

Figure 8.1: The power production consists of load following and regulation power. The load following power tracks the total system load and the regulation power compensates the small fluctuations of the total system load.

Figure 8.1 shows the principle of load following and regulation power. The total system load is tracked by the load following power and the regulation power compensates the small fluctuations. Nuclear and condensing power is relatively slow changing power sources and is often used as load following power. The regulation power sources have a short start up and regulation time to compensate the load changes in the grid.

8.1.1 Hydro and Thermal dominated power systems

Countries have the right to choose the power production plants and the type of power system is often depending on the resources of the country. For example countries with a large amount of
coal resources have often coal power plants. The power systems are divided into hydro power dominated systems and thermal power dominated systems.

The hydro power dominated system has a large amount of hydro power that is a good load following and regulation power source. Therefore the load following power is managed by a cheap and storable power source which contributes to a relatively constant electric price during the day.

Thermal dominated power systems consist mainly of coal and gas fired power plants. These power plants are used as both load following and regulation power. Gas responds relatively fast and is used for regulation power but also load following power. Coal on the other hand responds slower and is mainly used as base load and load following power. The electric price of thermal dominated power systems vary more during the day than hydro dominated systems. This depends on the slow upstart time of a coal fired power plant. The plant is not able to shut down during low demand periods since the upstart process takes time. The production rate is slightly reduced during low demand periods and this creates a surplus of electricity that will lower the electric price.

![Graph showing price structure](image)

**Figure 8.2: Illustration of price structure on the Nordic (hydro) and the Continental market (thermal) [9]**

Figure 8.2 shows the differences of electricity prices in hydro and thermal dominated power systems. The electricity price of a hydro dominated power system is relatively constant during the day compared to the thermal dominated power system where the variation between day and night are large. The power system of Stockholm is hydro dominated while the power systems of London and San Francisco are thermal dominated.

**8.1.2 Installed/available capacity and generated power**

The installed electricity generation capacity of more than 200 countries in the world is available at U.S. Energy Information Administration, EIA [32]. Statistics of the installed capacity is available and divided into the categories:

- Total generation capacity
- Hydro power
- Non-hydro electric renewable power
- Nuclear power
- Conventional thermal power
• Hydro electric pumped storage

The categories of non-hydro electric renewable and conventional thermal include a lot of different power sources and have to be divided into further categories. The non-hydro electric renewable categories are:

• Biomass power
• Waste power
• Geothermal power
• Solar PV power
• Solar thermal power
• Wind power
• Tide power

The conventional thermal power category:

• Oil-fired condensing power
• Coal-fired condensing power
• Gas-fired condensing power

These categories are possible to obtain with statistics of the total generated electricity from EIA and from the International Energy Agency, IEA [33]. The installed capacity is calculated from the total capacity and the proportion of generated power. The installed power of each source will get the same share in relation of the generated power.

The power plants are shut down during maintenance and other planned or unplanned stops. The power plants are not available at all time and capacity factors represent the utilization time.

The utilization time is defined as the planned production during a year divided by the installed capacity. This is equivalent to number of full load hours of the power plants and is presented in Table 8.1.

**Table 8.1: The utilization time and capacity factor of biomass, waste and fossil fuel condensing power plants [1], [41], [42].**

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Utilization time</th>
<th>Capacity factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ h / year ]</td>
<td>[ % ]</td>
</tr>
<tr>
<td>Coal</td>
<td>6000</td>
<td>68</td>
</tr>
<tr>
<td>Oil</td>
<td>6000</td>
<td>68</td>
</tr>
<tr>
<td>Gas</td>
<td>7446</td>
<td>85</td>
</tr>
<tr>
<td>Biomass</td>
<td>4500</td>
<td>51</td>
</tr>
<tr>
<td>Waste</td>
<td>6500</td>
<td>74</td>
</tr>
</tbody>
</table>

The production from renewable power sources, except biomass and waste power, is based on the average generated power during the previous years. The power is calculated by the total power production during a year divided by the number of hours during a year. The power is then
represented by MWh/h instead of MW. This calculation will not represent the seasonal variations of produced power.

The nuclear power production is in some countries a relatively large share of the total installed capacity. It is used as base load because of the slow regulation time and the capacity factors are important since the large share in the power system. A small change in the nuclear capacity factors could result in a relatively large deviation of the GHG model. The nuclear power is therefore based on the production during the year and is calculated in the same way as the renewable power sources.

The standard capacity factors for nuclear and renewable power sources are presented in Table 8.2 and are used if the capacity factors of a country not are available.

### Table 8.2: The utilization time and capacity factors of nuclear and renewable power plants [1], [41], [42].

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Utilization time [h/year]</th>
<th>Capacity factor [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>8000</td>
<td>91</td>
</tr>
<tr>
<td>Hydro</td>
<td>4000</td>
<td>46</td>
</tr>
<tr>
<td>Geothermal</td>
<td>7884</td>
<td>90</td>
</tr>
<tr>
<td>Solar PV</td>
<td>1752</td>
<td>20</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>1752</td>
<td>20</td>
</tr>
<tr>
<td>Wind</td>
<td>3000</td>
<td>34</td>
</tr>
<tr>
<td>Tide</td>
<td>2500</td>
<td>29</td>
</tr>
</tbody>
</table>

### 8.1.3 Electricity Production in Sweden

The Swedish electric power grid is divided into main, region and local grids and is part of the Nordic electric grid which consists of the neighboring countries, Norwegian, Finland and Denmark. The Nordic grid is also connected to Russian and European grids. [2] Svenska kraftnät, SVK, is the Swedish utility owner and provides the main grid. They are also and are responsible of the total energy balance in the system and import and export of electricity if necessary. About 170 companies own different parts of the regional grid where E.ON Elnät, Fortum Distrubition and Vattenfall Eldistrubrition are the largest companies.

The electric system main actors are [3]:

- **Electric producer** owns the power plants and produces electricity. The producers reports the planned production of the following 24 hours to the balancing power authority and have a opportunity to buy or sell balance power and electric certificates.
- **Utility owner** owns the power grid and is responsible for the electricity transport between the producer and the consumer. The utility owners measure the transferred electricity between the producer and the consumer and controls that the consumer gets the right
amount of transferred electricity. Because of that the utility owner may not produce, buy or sell electricity according to Swedish law.

- **Electric suppliers** buy electricity of the producer and sell to the consumer. The electric suppliers own sometimes the power plants and in that case are they also electric producers. The electric suppliers having the possibility to buy or sell balance power and electric certificates.
- **Electric consumer** buys electricity from the electric suppliers.
- **Electricity market** is where the participants are able to buy or sell electricity, balance power or energy certificates.
  - Sweden is divided in 4 areas with different regulation power [4]. Stockholm is part of area 3 and SVK published statistics of the electricity production from energy sources and regulation power.
  - The capacity factors, installed and available capacity and generated power for energy different sources is presented in Table 8.3.

### Table 8.3: The installed and available capacity of the Swedish power system.

<table>
<thead>
<tr>
<th>Power source</th>
<th>Installed capacity [MW]</th>
<th>Capacity factor [%]</th>
<th>Available capacity [MW]</th>
<th>Generated power [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>- coal</td>
<td>2144</td>
<td>68</td>
<td>1458</td>
<td>1705</td>
</tr>
<tr>
<td>- oil</td>
<td>1354</td>
<td>68</td>
<td>921</td>
<td>1077</td>
</tr>
<tr>
<td>- gas</td>
<td>1036</td>
<td>85</td>
<td>881</td>
<td>824</td>
</tr>
<tr>
<td>- biomass</td>
<td>2625</td>
<td>51</td>
<td>1339</td>
<td>8727</td>
</tr>
<tr>
<td>- waste</td>
<td>580</td>
<td>74</td>
<td>429</td>
<td>1929</td>
</tr>
<tr>
<td>- nuclear</td>
<td>9368</td>
<td>82</td>
<td>7645</td>
<td>66969</td>
</tr>
<tr>
<td>- hydro*</td>
<td>16358</td>
<td>46</td>
<td>7556</td>
<td>66188</td>
</tr>
<tr>
<td>- geothermal</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>- solar PV</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>- solar thermal</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>- wind</td>
<td>370</td>
<td>44</td>
<td>163</td>
<td>1430</td>
</tr>
<tr>
<td>- tide</td>
<td>0</td>
<td>29</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>- other sources</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total capacity</strong></td>
<td><strong>33835</strong></td>
<td></td>
<td><strong>20392</strong></td>
<td><strong>148849</strong></td>
</tr>
</tbody>
</table>
Figure 8.3: Available Capacity in Sweden

The available capacity of Sweden is presented in column 3 in Table 8.3 and in Figure 8.3. Hydro and nuclear power dominates the Swedish power system. Because of the large share of hydro power the power mix is varying depending on the available amount of water in the reservoirs. The available amount of water is varying during the year. A larger amount of water is available during winter and spring than during summer and autumn. These variations affect the power system by reduced or increased thermal power use.

Figure 8.4: The power production during the day. The hydro power is used as load following power
Historical statistics from SVK, Figure 8.4, shows that the load following power in Sweden is based on hydro power. There is no difference in load following power during the seasons [5]. Hydro power is used as load following power during the entire year. The nuclear, condensing and CHP are running with a relatively constant power during the day. The renewable energy sources produce electricity depending on the conditions of for example wind speed and irradiation [5].

The power has to be produced and consumed at the same time to stabilize the grid frequency. Disturbance will appear and cause power failure in some parts of the grid if the power balance is not obtained. SVK are main responsible of the power balance and in case of power deficiency the Swedish power reserve of 2000 MW is used. The power reserve consists of contracted energy suppliers and large consuming industries, which could start an extra power plant or reduce the consumption of the production.

Electric suppliers are able to maintain the economic responsibility of the power balance themselves or contract the power balance responsibility to another electric supplier. The responsible energy supplier have to regulate the own production or buying energy at the electricity market to maintain the hourly energy balance in the grid. The electric suppliers make a 24 hour consumption prognosis based on temperature, weather and the energy habits of the consumers. The consumption prognosis is reported to SVK which plans the energy production and consumption for the next 24 hours. The production units and load reducing industries of the Swedish power reserve are shown in Table 8.4. The fuels of the power reserve are oil and gas.

Table 8.4: The Swedish peak load power reserve administrated by Svenska kraftnät.

<table>
<thead>
<tr>
<th>Owner</th>
<th>Unit</th>
<th>Power (MW)</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maanenergi AB</td>
<td>Aros, block 3</td>
<td>243</td>
<td>Oil</td>
</tr>
<tr>
<td>Korsnäs AB</td>
<td></td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Karshamm Kraft AB</td>
<td>Karshamm, block 1</td>
<td>330</td>
<td>Oil</td>
</tr>
<tr>
<td>E.ON Brivalla</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sverige AB</td>
<td></td>
<td>220</td>
<td>Oil</td>
</tr>
<tr>
<td>Vattenfall AB Heat</td>
<td>Silte, Storningsund och Visby</td>
<td>396</td>
<td>Gas and Oil</td>
</tr>
<tr>
<td>Nordic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sum production</strong></td>
<td></td>
<td><strong>1309</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load reduction</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stora Enso AB</td>
<td>150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AV Reservefekt</td>
<td>70.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holmen AB</td>
<td>215</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belesa ScanDust AB</td>
<td>18.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rottneros Bruk AB</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INEOS Sverige AB</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goteborg Energi AB</td>
<td>73.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sum reduction</strong></td>
<td></td>
<td><strong>582.7</strong></td>
<td></td>
</tr>
</tbody>
</table>

| **Sum total** | 1891.7       |

Sweden’s power demand over 24h and the four seasons, Table 8.4, is obtained from SVK statistics [5].
Figure 8.5: Power Demand in Sweden over 24h for the four seasons

The electricity demand is largest during winter and is smallest during summer. This depends on the large need of heating and lighting of the houses during the winter in Sweden. The peak consumption during winter occurs in the afternoon and during the summer season the peak consumption occurs in the middle of the day.

The exchange between the neighboring countries affects the power production and GHG emissions. The exchange is investigated and included in the GHG model to increase the accuracy of the results.

The Swedish electricity grid is connected to the Scandinavian power grid, Nordel, which includes neighboring countries, Norway, Denmark and Finland. The Scandinavian power grid is connected to other grids in North Europe, Baltic and Russia.

The energy mix of electricity production in Europe and the other countries of Scandinavia consist of other power mixes than Sweden. The production mixes consists in most cases of a relatively large share fossil fuels burned in condensing power plants. The large amount of fossil fueled power plants implies in a large GHG emission.

The Swedish electricity power mix has a large share of renewable and nuclear power and relative low GHG emissions. Import and export is necessary to equal out surplus and deficiency between the grids.

Norway has a larger share of hydro power than Sweden and uses it as base load and load following power source.

The production mix of Finland consists of one half of renewable energy and nuclear power. The other half consists of thermal condensing power and CHP.

Denmark generation consists of condensing power, CHP and wind power where half of the total production is generated by coal-fired power plants.

Germany has an energy mix of 67% fossil fuels, 20% nuclear and 13% renewable energy.

The energy mix of Poland consists mainly of fossil fuels, 93 % coal.
The hourly exchange of electricity from Sweden to the neighboring countries is published at Nordpool spot market [7]. The total monthly exchange between the neighboring countries is obtained from SVK statistics [8].

**Figure 8.6: The power import and export of Sweden between the years 2004-2009. A positive value is import and a negative value is export**

The exchange during the seasons is shown in Figure 8.6 and is an average of the monthly exchange between the years 2004-2009.

Sweden exports energy to Denmark, Finland, Germany and Poland during most of the year. Sweden export electricity from Norway during spring and import during the rest of the year. Sweden exports electricity with Finland during spring and summer but Sweden imports a larger amount during autumn and winter. The import from Poland during autumn is relatively small.

The exchange has to be investigated by hour to be included in GHG model. The exchange between Sweden and the neighboring countries are shown in Figure 8.7. The effects of import and export between Sweden and Norway are relative low since the power mix is similar and mainly based on hydro power.
Figure 8.7: The hourly power total import and export between Sweden and Finland, Denmark, Germany and Poland during the seasons. Positive values are import and negative values are export of electricity

The Figure 8.7 shows the total power exchange in MWh/h between Sweden and the neighboring countries Finland, Denmark, Germany and Poland during 24 hours. The graphs are based on hourly data from Nordpool Spot during the years 2008 and 2009.

Sweden imports electricity during the night from the neighboring countries. The import during night could depend on the relatively large amount of electric heated buildings in Sweden and the low energy consumption of Germany, Poland and Denmark. The energy consumption increases during the day for these countries and import power from Sweden. Sweden has the largest exchange of power with Denmark and Norway of the three neighboring countries. The largest amount of imported electricity is during autumn and winter. The largest export is during spring and is probably depending on the hydro power and the large volumes of water in the reservoirs because of snow melting.

Sweden has hydro power as load following and regulation power source. That gives the opportunity to save hydro power and import electricity from the thermal dominated power systems when the import price is low. The saved electricity generated by hydro power could be exported when the export price is higher.

The hydropower dominance in Sweden leads to relatively stable prices during a typical day in contrast to the Continental prices with a wide variation between low demand periods and high demand and peak load periods [9].

The electric price of Sweden is available at Nordpool spot [10].
Figure 8.8 Electricity price at the Swedish Spot Market over 24h and seasons

The system price of Sweden is lower during night and higher during the day. The maximum peak price during the years 2008-2009 is about 1400 öre/kWh and the lowest electricity price could sometimes be negative, when the power system has a large surplus of electricity.

Statistics of the electric price of the neighboring countries is available at Nordpool spot [10], EEX [11] and the Polish power exchange [12]. The electric price in the Nordic countries is relatively similar to the Swedish electric price. The prices in Germany and Poland vary more than the Nordic electric price.

8.1.4 Electricity Production in United Kingdom

The capacity factors, installed and available capacity and generated power for energy different sources is shown in Table 8.5.

<table>
<thead>
<tr>
<th>Power source</th>
<th>Installed capacity [MW]</th>
<th>Capacity factor [%]</th>
<th>Available capacity [MW]</th>
<th>Generated power [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>- coal</td>
<td>28643</td>
<td>68</td>
<td>19477</td>
<td>138321</td>
</tr>
<tr>
<td>- oil</td>
<td>972</td>
<td>68</td>
<td>661</td>
<td>4692</td>
</tr>
<tr>
<td>- gas</td>
<td>34059</td>
<td>85</td>
<td>28950</td>
<td>164474</td>
</tr>
<tr>
<td>- biomass</td>
<td>1788</td>
<td>51</td>
<td>912</td>
<td>8114</td>
</tr>
<tr>
<td>- waste</td>
<td>723</td>
<td>74</td>
<td>535</td>
<td>3281</td>
</tr>
</tbody>
</table>
Figure 8.9: Available Capacity in United Kingdom

The available power of United Kingdom is presented in column 3 in Table 8.5 and in Figure 8.9 and is mainly based on thermal power. The share of renewable and nuclear power is about 1/6 of the total available capacity.

The load following power source in the United Kingdom power system is based on coal and gas. The hydro power is also used as load following power but due to the small amount the hydro power does not affect power system in general. The hydro power is probably used as regulation power which is needed in larger amounts during peak periods.

The power demand of UK is possible to obtain at, NETA [43] and National grid [44].
Figure 8.10: Power Demand in United Kingdom over 24h for the four seasons

The peak power demand occurs during the afternoon in all seasons except summer. The consumption of air condition appliances raises the electricity demand in the middle of the day.

The United Kingdom power grid is connected with power grids of Ireland and France and statistics of the import and export are available at bmreports [45]. The half hourly statistics are only available for the present month. The average exchange from UK to France and Ireland for 2 months, September and October 2010, is presented in Figure 8.11. The power mix of France has a large share of nuclear power and Ireland has mostly fossil fuels.

Figure 8.11: The import and export from United Kingdom to France and Ireland

Figure 8.11 shows that UK imports electricity during night and afternoon from France but in the middle of the day UK exports to France. The nuclear power in France is slow regulated and is not shut down during the night. This contributes to a surplus of electricity and the electric price in France is lowered.

The UK electric price is obtained from Bmreports [45]. The statistics for one day are available. The statistics are not so detailed because of the time demanding work to collect the data.

Electric prices from Ireland are obtained from the Single Electricity Market Operator, SEMO [46]. The French electric prices are obtained from European energy exchange, EEX [11].

The exchange rate of one Euro and one UK pound is for the simplicity set to 10 SEK. [47]
The system price is lower during night and higher during the day. The peak price is about 700 öre/kWh and the lowest price is about 18 öre/kWh.

### 8.1.5 Electricity Production in California, US

The capacity factors, installed and available capacity and generated power for energy different sources is shown in Table 8.6.

#### Table 8.6: The installed and available capacity of the California power system.

<table>
<thead>
<tr>
<th>Power source</th>
<th>Installed capacity [MW]</th>
<th>Capacity factor [%]</th>
<th>Available capacity [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>- coal</td>
<td>445</td>
<td>68</td>
<td>303</td>
</tr>
<tr>
<td>- oil</td>
<td>531</td>
<td>68</td>
<td>361</td>
</tr>
<tr>
<td>- gas</td>
<td>37235</td>
<td>85</td>
<td>31650</td>
</tr>
<tr>
<td>- biomass</td>
<td>466</td>
<td>51</td>
<td>238</td>
</tr>
<tr>
<td>- waste</td>
<td>356</td>
<td>74</td>
<td>263</td>
</tr>
<tr>
<td>- nuclear</td>
<td>4390</td>
<td>91</td>
<td>3995</td>
</tr>
<tr>
<td>- hydro*</td>
<td>10095</td>
<td>46</td>
<td>4644</td>
</tr>
<tr>
<td>- geothermal</td>
<td>1978</td>
<td>90</td>
<td>1781</td>
</tr>
<tr>
<td>- solar PV</td>
<td>15</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>- solar thermal</td>
<td>344</td>
<td>20</td>
<td>69</td>
</tr>
<tr>
<td>- wind</td>
<td>2367</td>
<td>35</td>
<td>829</td>
</tr>
</tbody>
</table>
Figure 8.13 Available Power of California

The available power of California is presented in column 3 in Table 8.6 and in Figure 8.13 and is mainly based on gas fired power. The share of renewable and nuclear power is about 1/5 of the total available capacity. The power system of California imports ¼ of the electricity demand.

The load following power and regulation power is based on gas fired power. The gas fired power is easily controlled and thereby it is used for both load following and regulation power.

The power demand of United States and California are available at Federal Energy Regulation Commission, FERC [48].
Figure 8.14: Power Demand in California over 24h for the four seasons

The highest power demand occurs in the summer and the lowest occurs in winter and spring. The air condition appliances are used a lot during the summer and contribute to the large electricity consumption. The difference between winter and spring is a power peak in the evening contributed by the used lamps.

The FERC presents a demand and electric price forecast for one day ahead and is available at the webpage [48].

California imports approximately ¼ of the electricity demand during a year [48]. The California electricity grids are connected to two neighboring grids, the Northwest and the Southwest power systems. The Northwest power mix is mainly based on hydro and gas power and generates a large surplus of electricity that could be exported [48]. The Southwest power system is based on gas fired power and generates also a large surplus of electricity. The transfer capacity from the neighboring powers systems to California are fully utilized during the high demand periods in the summer [48].

Figure 8.15 Net import of electricity to California over seasons

Figure 8.15 shows the net import of electricity to California and is based on statistics from California ISO [49]. Electricity is imported during all hours of the day and the year because the surplus electricity generation in the neighboring power systems.
The electric price of California is also available at the FERC [48] and the electric price in Southwest is available at Southwest Power Pool [50].

The exchange rate of one USD is assumed 8 SEK. [47]

![California Electricity Spot Price over seasons and 24h](image)

Figure 8.16 California Electricity Spot Price over seasons and 24h

The US electric prices are relatively low compared to the European prices.

8.2 Electricity Production in the Future

The future power generation depends on a number of parameters mainly the political instruments that affect the power generation. The Nordic power grids are connected to north Europe power grids that include Germany and Poland. A study of ELFORSK 08:30 treat the effects of changed electric consumption affects the GHG emissions in the future. There is a difficult task to prospect the future production, consumption and the political instruments and therefore different scenarios where made.

The present and future energy production mixes of the Nordic and north Europe is investigated and the nuclear power is assumed of shutting down in Germany and Sweden when the power plants reach their maximum life time. New nuclear power is assumed to be build in the future.

In the study Sweden increase or decrease the electricity consumption by 5 TWh/year. Where 2,5 TWh/year is household electricity and 2,5 TWh/year is industry electricity. The largest increase of production is located in Germany and Poland since the grids are connected.

The contribution from the different regions is shown in Figure 8.17 and a large amount of the GHG emissions are located outside Sweden.
The result due to an increase of 5 TWh/year electricity in Sweden is calculated to be 670 kg GHG/MWh generated in north Europe where the Swedish GHG emission of 30 kg GHG/MWh is included. [13] If Sweden reduces the consumption of 5 TWh/year instead the result is calculated to be a reduction of 670 kg GHG/MWh in north Europe where the Swedish amount of reduction of 80 kg GHG/MWh is included. [13]

Figure 8.18 shows the production energy mix of the reduced 5 TWh/year energy consumption where coal, oil and gas are the largest parts.

These results are used as reference numbers in the ELFORSK 08:30 are obtained without any changes in political instruments from today. The political instruments are most likely going to change in the future but today it is impossible to know how. Therefore a number of scenarios are developed. The results of the different scenarios are shown in Table 8.7.
Table 8.7: The specific GHG emissions in north Europe of different scenarios depending on the political instruments

<table>
<thead>
<tr>
<th>Specific GHG emissions [kg GHG / MWh]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (political instruments of today)</td>
<td>670</td>
</tr>
<tr>
<td>Higher fossil fuel prices</td>
<td>780</td>
</tr>
<tr>
<td>Higher GHG prices</td>
<td>160</td>
</tr>
<tr>
<td>Larger quota of electric certificate</td>
<td>640</td>
</tr>
<tr>
<td>Reduced total consumption in north Europe</td>
<td>640</td>
</tr>
<tr>
<td>Limit of total GHG emissions in north Europe</td>
<td>0</td>
</tr>
</tbody>
</table>

The specific GHG emissions in Sweden are between -20 and 80 kg GHG / MWh for all scenarios. This result is determined with the assumption of the settlement of nuclear power in Germany and Sweden with a total amount of 200 TWh. If the nuclear power is replaced with new nuclear power during this period of time the power generated by gas, oil and coal will be reduced. The specific GHG emissions in north Europe will be reduced to about 480 kg GHG/ MWh.
### CHANGE HISTORY

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<th>Chapter</th>
<th>Description</th>
<th>Date / Dep. / Name</th>
</tr>
</thead>
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### REVIEW HISTORY

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