Fully Renewable Electricity Scenarios for Sweden on a Cost Optimal basis

Erika Capobianchi

*Sustainable Energy Engineering* Master’s Thesis

Supervisor: Constantinos Taliotis

Examiner: Mark Howells

School of Industrial Engineering and Management
Year 2017
EGI_2017_0116MSC EKV1236
Table of Contents

Abstract ............................................................................................................................................................. 3
1. Introduction ............................................................................................................................................... 4
   1.1 Literature Review .............................................................................................................................. 6
2. The Swedish Energy System ...................................................................................................................... 8
   2.1 Electricity ........................................................................................................................................ 8
   2.2 Heating ......................................................................................................................................... 11
   2.3 Policies and targets .......................................................................................................................... 12
3. Method .................................................................................................................................................... 14
   3.1 Introduction to OSeMOSYS ............................................................................................................. 14
   3.2 The Energy Model .......................................................................................................................... 15
      3.2.1 Scenarios ............................................................................................................................... 25
4. Results and Discussion ............................................................................................................................. 26
   4.1 Scenario 1 ..................................................................................................................................... 26
   4.2 Scenario 2 ..................................................................................................................................... 29
   4.3 Scenario 3 ..................................................................................................................................... 32
   4.4 Scenario 4 ..................................................................................................................................... 34
   4.5 Scenario 5 ..................................................................................................................................... 36
   4.6 Emissions ....................................................................................................................................... 38
   4.7 Costs ............................................................................................................................................ 38
5. Conclusions .............................................................................................................................................. 41
6. References ............................................................................................................................................... 42
Appendix A .................................................................................................................................................. 44
Appendix B ................................................................................................................................................... 45
Abstract

The importance of reducing greenhouse gases to tackle climate change has been widely discussed. Leading climate scientists warn that we immediately have to take action to avoid the dangerous effects that would be generated if the global temperature rises by 2°C above pre-industrial levels. Additional anthropogenic carbon dioxide emissions are accelerating the changes in the Earth’s climate, therefore reducing carbon footprint is a principal goal of these times. The energy industry is one of the biggest contributor to carbon dioxide emissions. Renewable energy technologies will play a central role in the future electricity system and their business potential in the future energy market appears in line with a low carbon economy. The present study analyses the evolution of renewable energy technologies in the electricity and heating market for Sweden on a cost optimal basis. An iterative process is carried out throughout the research with the help of a modelling framework, OSeMOSYS, and a calculation file based on a comparison with historical data for electricity generation. Results show how the Swedish electricity and heating system could be dominated respectively by wind and biomass due to the large resource availability.
1. Introduction

The importance of reducing Carbon Dioxide emissions has been largely discussed among the scientific community and it is becoming everyday more relevant [1]. The atmosphere and the oceans have become warmer, the amount of snow and ice has decreased, sea levels have risen and the concentration of greenhouse gases increased [2].

The Intergovernmental Panel on Climate Change (IPCC) stated that the Earth’s climate system is without any doubt getting warmer and that the process of warming in the past 50-60 years is being accelerated by human contributions [3]. In fact, as the levels of CO₂ and Greenhouse gases grow, the heat is captured in the Earth’s atmosphere and the global temperature rises.

The Paris Agreement brings several nations into a cause of common interest to tackle climate change and adapt to its effects, helping developing countries in doing so [4]. The main goal is to empower global action in fighting climate change by keeping the temperature increase within this century below 2°C while pursuing efforts to limit the temperature rise even below 1.5 °C. This further strengthens the necessary transition towards a low carbon economy.

Therefore, decreasing carbon emissions is one of the main issues that countries have to face. The energy industry is by far one of the largest contributor to greenhouse gases emissions. Most sectors of the energy system are highly reliant on the use of conventional fossil fuels such as oil, coal and gas, which are responsible for climate change. But since they are limited, their depletion is occurring rapidly; supplies of cheap, conventional oil and gas are dropping while our energy demand is increasing and our reliance on fossil fuels might not be supported [5].

In the electricity industry, alternatives that contribute to lower emissions include nuclear power and fossil-fired plants with carbon capture and storage [6]. Although the former has different international issues of public acceptance, the latter has not yet been developed as a business. Hence, renewable energy technologies will play a central role in the transition to a low carbon economy. Development of renewable technologies, such as solar or wind, represents a good way of dealing with climate mitigation.

A fully sustainable and renewable power supply is an optimal way to secure energy for all and avoid environmental catastrophe [5]. Renewable energy sources offer the potential to transform the quality of life and improve the economic prospects of billions of people with lower environmental
impact. They play an important role in reducing greenhouse gases emissions and at the same time their use reduces the demand for fossil fuels [7]. Another benefit relates to energy security; renewable energy sources are typically domestic resources that can consequentially reduce fuel imports. The resources that are most commonly used can be classified into Biomass, Hydropower, Geothermal, wind and solar.

Biomass is a particular resource as it can be found in three different states: solid, liquid and gaseous. For this reason, its employment is not only restricted to electricity generation but it can be applied to generate other forms of energy and it can be easily stored. Examples of biomass are found in wood, waste, ethanol and biodiesel.

With the increasing and visible effects of climate change, countries are beginning to develop responses to protect citizens and economies promoting renewable energy. The Global renewable power generating capacity saw its largest annual increase ever in 2015, with an estimated 147 GW of renewable capacity added [8]. By the end of 2015, renewables reached an estimated 23.7% of electricity generation, with hydropower providing about 16.6% (Figure 1).

Asia installed the most renewable power generating capacity during 2015 in the global share, of which the most accounts for hydropower. In Europe between the years 2000-2015 the share of renewable power capacity increased from 24% to 44%, and in 2015, renewables were Europe’s largest source of electricity. Sweden plays an important role as among all the European countries has set an economy based on low carbon emissions and renewable energy; most of the electricity generation is led by hydropower while other renewable based technologies are growing. A deeper insight of the Swedish energy system will be given in the present study with a special focus on
electricity and its way toward a fully renewable electricity generation. The research aims to model a 100% renewable electricity system for Sweden on a cost optimal and market oriented basis; the heating sector is also taken into consideration as it affects the way electricity is generated. Tidal energy and geothermal are excluded from the research and nuclear is assumed to be phased out at the latest by 2045, since it is not renewable energy.

1.1 Literature Review

Previous and recent studies have analysed the transition of energy systems. Many sources are reviewed for this research but the ones that had a bigger impact and are mainly focused on Sweden are listed in this section of the thesis.

*The Global Status Report 2016* [8] presents a general overview of the energy systems and electricity generation worldwide, showing how the share of renewable energy is changing around the Globe. The report presents how the latest years saw continued advances in renewable energy technologies as well as energy efficiency improvements.

More focus is given to the Nordic countries in the report *Nordic Energy Technology Perspectives 2016* [9], which provides a case study on the road towards national climate targets and a carbon neutral energy system.

In the paper *Four Futures* [2] the attention is centred on Sweden, where the Swedish Energy Agency provides a view on four possible different scenarios as part of a social, environmental, economical and political context. Each future has a driving force that leads the change after the year 2020. Key findings confirm that Sweden has good potential for producing electricity with both low emissions and low costs, thanks to convenient access to natural resources.

In the report *Sveriges Framtida Elproduktion* developed by IVA [10] alternative ways are investigated toward a fossil fuel free power generation. Four scenarios are presented and the implications discussed respectively for more wind and solar, more biomass, more nuclear and at last more hydropower scenarios. Conclusions support Sweden and its ability to be fossil independent by the year 2050 in the electricity market, satisfying the internal demand exclusively by internal resources.

*Electricity production in Sweden* [11] explores technical properties of the different energy sources in order to optimise the efficiency of the whole electricity system; it also gives a perspective on how
to manage the intermittency of wind power generation in the system. A substantial expansion of wind power could have a negative impact on its own profitability for investors; it produces the most in windy days which lowers the price of electricity for it than the average on the spot market.

The heating sector is also explored as it affects electricity generation; the main reference study for the present research is *The Heating Market in Sweden* [12] in which the purpose is to draw a picture of the Swedish heating market proposing opportunities as well as challenges for this sector.
2. The Swedish Energy System

Sweden has focused its long term goals on an economy based on sustainable energy. Today it is recognised as one of the leading IEA (International Energy Agency) member countries in terms of low-carbon intensity and high share of renewable energy in the total energy supply, with a big quota of hydro, solid biofuels and onshore wind [13].

The Swedish energy system is both based on domestic renewable sources and fossil fuel imports such as oil and natural gas mainly for the transport sector [14]. The electricity generation is dominated by hydropower and nuclear power, while wind power is rapidly increasing as well as the employment of biomass for both heat and power.

Figure 2 The Energy System [14]

The progress made up to now is the result of strong national as well as European political efforts, including high carbon dioxide and energy taxation, the Emission Trading Scheme (ETS) and the promotion of renewables within the electricity certificate system.

The present chapter will provide the reader with a deeper insight of the electricity and heating system for Sweden. A general overview will be given for these two sectors as they strongly influence each other affecting the electricity generation.

2.1 Electricity

Electricity is the dominant form of energy used in Sweden [13]; Sweden’s electricity generation is near to be carbon-free as it is mainly based on nuclear and hydro. This gives the country the second
place, after Switzerland, in renewable power share among all other IEA member states. Its total electricity generation is more than any of the other Nordic countries accounting for 63% share of renewable as for 2014, with the target to be 100% renewable by 2040 [13], [15].

Sweden’s largest generation source are hydropower and nuclear, with respectively 47.1% and 34.2% of share in electricity production for 2015 [16]. Nuclear power supply has been slowly declining over the years as a consequence of political decisions that demand a higher share of renewables and the decommissioning of nuclear reactors. Hydropower supply, on the other hand, has been stable in the recent years but can vary depending on weather conditions (Figure 3).

Wind power is the technology that experienced the biggest growth; onshore installations have increased by 25% from 2014 to 2015 with more than 5 GW installed capacity, surpassing Denmark, reaching 10.2% of the share while biomass and waste account for 6% [9].

![Figure 3 Swedish Electricity Production 2015](image)

As electricity generation and transmission capacity have been expanded over the years, electricity transmission between the Nordic countries has increased [17]. The consequence is an evolution of a dynamic market, Nord Pool, where power can be bought or sold across areas and countries more easily. The Swedish electricity market is integrated in the Nordic Market and hence interconnected with several countries to exchange their power. As of nowadays nine countries are part of the Nord Pool market and are constantly trading electricity with their neighbours [11].

Electricity generation remains the pilaster of the Nordic energy system, as it reflects the high level of development and energy usage of the Nordics [9]. Sweden is the country that has a central role in the Nordic electricity market as its volume of electricity generation, presented in Figure 4, is the biggest. It is evident from the picture how Sweden is highly dependent on nuclear and hydro, with
a considerable share of biomass and wind. Norway, as a comparison, is almost fully dependent on hydropower.

As of nowadays Sweden has all the potential to develop an electricity system based exclusively on renewables. The profile of demand though plays a big role in the transition to renewables as demand needs to be met by supply. Seasonal electricity consumption patterns vary from region to region and most of them have their peak load in the winter time when the weather is colder and the days are shorter. This requires more electricity for lighting and for heating devices running on electricity [18].

On the other hand, during summer time, electricity consumption tends to be less as the length of the daytime increases and electricity for lighting is not much needed. An example of the electricity demand for the year 2015 is shown in Figure 5 [19], while in Figure 6 two typical days are presented in detail respectively for winter (January the 4th) and summer (July the 6th).
At first look it is evident how electricity consumption differs from winter to summer time; demand during summer days is only two thirds of the one for winter time.

2.2 Heating

The heating sector in Sweden is among the largest energy sectors along with electricity [12]. Space and water heating represents one fourth of Sweden’s total energy consumption. The biggest consumers are single family houses, multi family houses and industries.

In the present study it is very important to consider the role of the heating sector. Almost 50% accounts for district heating while most of the rest accounts for electricity based technologies, with 20% of heat pumps. The importance of the heating sector in a fully renewable electricity market is directly connected to the district heating system (DH); a big share of the heating provided through district heating derives from biomass boilers, waste incineration and Combined Heat and Power (CHP) plants which generate electricity and heat at the same time. Hence, if the heating demand can partly be satisfied while producing electricity, CHP plants are more profitable as the overall efficiency increases (heat and power are supplied simultaneously). If the heating demand is not taken into consideration in the analysis, CHP would be too expensive as an option to only generate electricity since cheaper technologies can satisfy the electricity demand.

Nevertheless, the heat demand is not only important for CHP but also for electrically based technologies. Almost one third of the heating demand is based on electricity; heat pumps and other
electrical heating devices require electrical power to work and their employment will affect the national electricity demand level and profile.

### 2.3 Policies and targets

Sweden is a parliamentary democracy with a constitutional monarchy under the king of Sweden and head of state King Carl XVI Gustav [13]. The state is composed of 21 administrative counties. The central government develops energy policies with the support of local and national authorities. Since Sweden joined the European Union in 1995 it is bound to the EU framework which sets requirements for energy policy; those are particularly headed for energy efficiency, Renewable Energy, electricity and gas market, energy taxation, environment and GHG emissions.

The responsible authority for the implementation of the energy policy in Sweden is the Swedish Energy Agency [15]. The agency is in charge of gathering energy statistics and conducting policy analysis, modelling projections, electricity certificate system, promotion of RE and the administration of the projects under the Kyoto Protocol.

Sweden's energy policy is guided by two government Bills (2008/09:162 and 163). The key policy based on 20/20/20 EU target is set by the bill “En integrerad energi- och klimatpolitik”, integrated climate and energy policy. Sweden sets its goal for short and long term as:

- **Short- to medium-term targets for 2020:**
  - 40% reduction of GHG compared to 1990 levels to be achieved outside the Emission Trading Scheme (ETS);
  - Minimum of 50% of Renewable Energy in the final energy consumption;
  - Minimum share of 10% of RE in the transport sector;
  - 20% increase of energy efficiency compared to 2008.

- **Long term targets:**
  - Fossil fuel independent vehicle fleet by 2030;
  - Increase of Co-generation, wind and other renewable sources in electricity production;
  - Sustainable energy supply with zero net emissions of GHGs by 2050.
The goal of Swedish energy policy is to reach 100% renewable electricity generation by 2040 based on the *agreement* on Sweden’s long-term energy policy [20]. The target of the political agreement states that Sweden has to reach zero net emissions by the year 2045 and 100% renewable electricity generation by 2040; this target, though, does not imply banning nuclear power, nor closing nuclear power plants by 2040 [21]. These political statements might seem contradictory, nevertheless nuclear reactors are planned to be decommissioned in the year 2045 [22].
3. Method

This section of the dissertation describes the approach followed in the thesis giving an overview of the tools chosen. The present study is conducted at the company Svebio, Stockholm. A literature review within the scope is carried out in the preliminary stage. The main tool used to accomplish the study is the optimization framework OSeMOSYS. A previous similar model developed by Henke [23] has been used as a basis to start new calculations oriented towards a 100% renewable electricity system for Sweden; the model contained information regarding fossil-fuels based technologies developed up to now for the Nordic countries and possible evolution. New fuels and renewable technologies with relative costs have been inserted and implemented to develop a fully renewable electricity system.

An iterative process is carried out throughout the research; the results are compared to historical data for 2015, scaled up for each particular configuration and capacity obtained to check how many hours generation exceeds demand, assuming no trade with neighbouring countries. The electricity export is assumed to be zero as the worst case scenario; this has been done with the assumption that the member countries of the Nordic Market will develop themselves renewable energy technologies and it would not be possible to export electricity at the time it exceeds in Sweden since almost everyone will be generating more at the same time due to similar weather conditions.

The calculation is done with the help of an excel file counting the specific hours of overproduction for each layout. A minimum amount of hydropower and industrial CHP production is taken into account and set to 4,5 GW while the capacity factor of wind and solar power increased by 60% due to technology improvements [24]. The capacity of wind is then adjusted for each specific layout until it reaches the targeted maximum hours of overproduction; then the model is run again with those values.

3.1 Introduction to OSeMOSYS

Energy system models are made to investigate a variety of assumptions under technical and economic perspectives. The outputs may be different according to the type of framework it is used to analyse the scenarios. OSeMOSYS is in this sense a long-term optimisation framework. It is a tool designed to inform the development of national and regional energy strategies. As a linear
optimisation model it calculates the results based on the least cost solutions minimizing the total discounted costs [25].

All energy sectors can be considered including heat, electricity and transport and it is possible to define flexible technologies comprising all chains from resource extraction up to the energy final use in appliances. In its standard form, OSeMOSYS assumes optimal foresight and perfect competition on energy markets. In the present study the focus is directed to the electricity and heating sectors for Sweden.

3.2 The Energy Model

The model developed on OSeMOSYS is based on a previous study made by Henke [23]. The model has then been changed and adapted to Sweden. Since the main focus of this research is to develop an electricity system for Sweden which is 100% renewable and cost optimized, as well as market oriented, the technologies using renewable sources have been elaborated and enriched with specific details; new technologies are added while other fossil fuel based technologies deleted. In the present section the specifics of the model are shown in detail:

Timeslices

Since the demand and production sides are different in the different periods of the year, Time slices have been created. In the time slices the first division is directly linked to the months of the year; the highest consumption patterns within the months are mainly due to lighting and heating in the winter times. The second division has been done in three period of the daytime based on the electricity consumption in the specific hours for day (medium), night (low) and peak (high).

For each month specific hours of the day are extracted in relation to the specific consumption at a certain hour: if the electricity consumption at a certain hour is high, then that hour is considered as peak hour for that specific month; if the consumption is low, the hour will be linked to a night hour and so on. Later, all the hours for each specific month and daytime will be summed up and divided for the total hours of the year to obtain the particular value of the time slices.

In order to decide exactly which are the hours of the daytime to be considered peak, night and day, it has been analysed the electricity consumption for the year 2015 [26]. Figure 7 and Figure 8 show an example of the electricity demand respectively during winter period and summer period. The
curves presented describe the sum of the demand for a specific month in a specific hour; for example, at the time 01:00 the corresponding point on the graph will present the sum of the electricity demand of every day of the month at that exact hour. This way, it is possible to decide on average which are the hours for each (slice) *daytime*.

![Figure 7 Sum of January Electricity Demand](image)

![Figure 8 Sum of July Electricity Demand](image)

It is again evident how the electricity consumption differs from winter to summer time. Both of the distributions though have their peak during working hours and, for winter, even right after working time when people gets back home, turn on lighting and heating devices, cook dinner and do their household chores. In Table 1 it is presented in detailed how the division has been made and which are the specific hours of the day chosen for each time slice; the value shown is considered to be the share of the year.
<table>
<thead>
<tr>
<th>Timeslice</th>
<th>Value</th>
<th>Tot hrs tmslc/ month</th>
<th>hrs/day</th>
<th>specific hours of the day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan day</td>
<td>0.031849</td>
<td>279</td>
<td>9</td>
<td>6-7-13-14-15-16-21-22-23</td>
</tr>
<tr>
<td>Jan peak</td>
<td>0.031849</td>
<td>279</td>
<td>9</td>
<td>8-9-10-11-12-17-18-19-20</td>
</tr>
<tr>
<td>Jan night</td>
<td>0.021233</td>
<td>186</td>
<td>6</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>Feb day</td>
<td>0.031963</td>
<td>280</td>
<td>10</td>
<td>6-7-13-14-15-16-20-21-22-23</td>
</tr>
<tr>
<td>Feb peak</td>
<td>0.025571</td>
<td>224</td>
<td>8</td>
<td>8-9-10-11-12-17-18-19</td>
</tr>
<tr>
<td>Feb night</td>
<td>0.019178</td>
<td>168</td>
<td>6</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>March day</td>
<td>0.028311</td>
<td>248</td>
<td>8</td>
<td>6-7-14-15-16-17-22-23</td>
</tr>
<tr>
<td>March peak</td>
<td>0.035388</td>
<td>310</td>
<td>10</td>
<td>8-9-10-11-12-13-18-19-20-21</td>
</tr>
<tr>
<td>March night</td>
<td>0.021233</td>
<td>186</td>
<td>6</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>April day</td>
<td>0.037671</td>
<td>330</td>
<td>11</td>
<td>6-7-14-15-16-17-18-19-20-22-23</td>
</tr>
<tr>
<td>April peak</td>
<td>0.023973</td>
<td>210</td>
<td>7</td>
<td>8-9-10-11-12-13-21</td>
</tr>
<tr>
<td>April night</td>
<td>0.020548</td>
<td>180</td>
<td>6</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>May day</td>
<td>0.046005</td>
<td>403</td>
<td>13</td>
<td>6-7-8-14-15-16-17-18-19-20-21-22-23</td>
</tr>
<tr>
<td>May peak</td>
<td>0.017694</td>
<td>155</td>
<td>5</td>
<td>9-10-11-12-13</td>
</tr>
<tr>
<td>May night</td>
<td>0.021233</td>
<td>186</td>
<td>6</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>June day</td>
<td>0.047945</td>
<td>420</td>
<td>14</td>
<td>6-7-8-15-16-17-18-19-20-21-22-23-24-1</td>
</tr>
<tr>
<td>June peak</td>
<td>0.020548</td>
<td>180</td>
<td>6</td>
<td>9-10-11-12-13-14</td>
</tr>
<tr>
<td>June night</td>
<td>0.013699</td>
<td>120</td>
<td>4</td>
<td>2-3-4-5</td>
</tr>
<tr>
<td>July day</td>
<td>0.049543</td>
<td>434</td>
<td>14</td>
<td>6-7-8-9-15-16-17-18-19-20-21-22-23-24</td>
</tr>
<tr>
<td>July peak</td>
<td>0.017694</td>
<td>155</td>
<td>5</td>
<td>10-11-12-13-14</td>
</tr>
<tr>
<td>July night</td>
<td>0.017694</td>
<td>155</td>
<td>5</td>
<td>1-2-3-4-5</td>
</tr>
<tr>
<td>August day</td>
<td>0.049543</td>
<td>434</td>
<td>14</td>
<td>6-7-8-9-15-16-17-18-19-20-21-22-23-24</td>
</tr>
<tr>
<td>August peak</td>
<td>0.017694</td>
<td>155</td>
<td>5</td>
<td>10-11-12-13-14</td>
</tr>
<tr>
<td>August night</td>
<td>0.017694</td>
<td>155</td>
<td>5</td>
<td>1-2-3-4-5</td>
</tr>
<tr>
<td>Sept day</td>
<td>0.037671</td>
<td>330</td>
<td>11</td>
<td>6-7-8-15-16-17-18-19-21-22-23</td>
</tr>
<tr>
<td>Sept peak</td>
<td>0.023973</td>
<td>210</td>
<td>7</td>
<td>9-10-11-12-13-14-20</td>
</tr>
<tr>
<td>Sept night</td>
<td>0.020548</td>
<td>180</td>
<td>6</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>Oct day</td>
<td>0.031849</td>
<td>279</td>
<td>9</td>
<td>7-13-14-15-16-17-21-22-23</td>
</tr>
<tr>
<td>Oct peak</td>
<td>0.028311</td>
<td>248</td>
<td>8</td>
<td>8-9-10-11-12-18-19-20</td>
</tr>
<tr>
<td>Oct night</td>
<td>0.024772</td>
<td>217</td>
<td>7</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>Nov day</td>
<td>0.023973</td>
<td>210</td>
<td>7</td>
<td>7-8-14-15-21-22-23</td>
</tr>
<tr>
<td>Nov peak</td>
<td>0.034247</td>
<td>300</td>
<td>10</td>
<td>9-10-11-12-13-16-17-18-19-20</td>
</tr>
<tr>
<td>Nov night</td>
<td>0.023973</td>
<td>210</td>
<td>7</td>
<td>24-1-2-3-4-5</td>
</tr>
<tr>
<td>Dec day</td>
<td>0.021233</td>
<td>186</td>
<td>6</td>
<td>7-8-15-21-22-23</td>
</tr>
<tr>
<td>Dec peak</td>
<td>0.038927</td>
<td>341</td>
<td>11</td>
<td>9-10-11-12-13-14-16-17-18-19-20</td>
</tr>
<tr>
<td>Dec night</td>
<td>0.024772</td>
<td>217</td>
<td>7</td>
<td>24-1-2-3-4-5</td>
</tr>
</tbody>
</table>

**Table 1 Timeslices division**

**Technologies:**

The technologies in the model are based on actual installed capacity for electricity generation and heating, both fossil fuel based and not. Though, since the focus of the research is to develop a fully
renewable energy system, more details are presented here for the renewable side of electricity and heat generation:

1. **Hydro**

The actual installed capacity of Hydro in Sweden provides close to half of Sweden’s baseload power [11]. The plants are divided in mini hydro (up to 1MW), small Hydro (1 – 10 MW) and large Hydro (>10 MW). The residual capacity of each size plant is calculated from Platts database [27], where the capacity of each plant is summed up respectively for mini, small and large hydro for a total of 16.7 GW. Capital and fixed costs for this technology are taken from IEA-ET SAP [28] and presented in Table 2.

The electricity generation from hydropower has been maintained constant in the model with no possibility of enlargement; the assumption is built upon the fact that no more investment will be done to expand this technology, but only renovation of existing plants [29]. In Figure 9 a representation of a hydropower plant is showed.

<table>
<thead>
<tr>
<th>HYDROPOWER</th>
<th>Mini</th>
<th>Small</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M$/GW)</td>
<td>5000</td>
<td>4500</td>
<td>4000</td>
</tr>
<tr>
<td>Fixed costs M$/GW</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>2020</td>
<td>2030</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>2020</td>
<td>2030</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>2020</td>
<td>2030</td>
</tr>
</tbody>
</table>

*Table 2 Hydropower Costs [28]*

*Figure 9 Example of a Hydropower plant*
2. **Solar**

Electricity generation from solar power (Figure 10) amounts to ca. 0.09 TWh with an installed capacity of 0.104 GW [30]. The highest generation from solar comes during the summer, when the need is the lowest, therefore no additional value is added from this technology. In order to be productive, solar cells have to be connected to battery systems for electricity storage. The costs of this technology are taken from NREL database [31] and presented in Table 3; only three step years are showed, the reader should consider that the prices considered in the model are decreasing each year as the technology gets cheaper.

![Figure 10 Example of Solar PV Panels](image)

<table>
<thead>
<tr>
<th>SOLAR PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>Capital costs (M$/GW)</td>
</tr>
<tr>
<td>Fixed costs M$/GW</td>
</tr>
</tbody>
</table>

**Table 3 Solar PV costs** [31]

3. **Wind**

Wind is by far the renewable source that has grown the fastest in Sweden in the latest years and has a big potential in the transition to 100% renewables. The total installed capacity of wind was 6.52 GW at the end of 2016 with an actual generation of 15.4 TWh depending on wind conditions and when installations are made [32]. The number of turbines was 3386 at the end of the same year of which 3312 onshore and 74 offshore with an installed capacity of respectively 6.33 GW and
0.19 GW. Capital costs, fixed and O&M are taken from Energistyrelsen [33] and presented in Table 4 for the year 2015, 2020 and 2030. All the costs include grid connection.

<table>
<thead>
<tr>
<th>WIND</th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small (&lt; 25 kW)</td>
<td>Large</td>
</tr>
<tr>
<td>Capital costs (M$/GW)</td>
<td>4240</td>
<td>4028</td>
</tr>
<tr>
<td>Fixed costs M$/GW</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Variable O&amp;M (M$/PJ)</td>
<td>1.17778</td>
<td>1.118889</td>
</tr>
</tbody>
</table>

Table 4 Wind Power Costs [33]

It is noticeable how, comparing the technologies for the same size, onshore wind gets cheaper in the future while offshore still remains expensive and less competitive on the market. Figure 11 illustrates an example of onshore wind power.

![Figure 11 Example of Onshore Wind Power](image)

4. **CHP bio and waste**

Combined heat and power (CHP), or cogeneration, is a system that generates electricity while using the residual heat generated in the process for residential heating or production of hot water and steam for other applications [28]. It can make a significant contribution for energy efficiency measures.
Combined heat and power plants are usually used for district heating in Sweden and dimensioned on the basis of the heat requirements in the district heating system. As previously described, electricity and heat are generated at the same time. CHP became more attractive since the energy certificate was introduced. The fuel usually used for these plants is woodchips with a price for Sweden of 5.44 USD/MWh [15]. Capital, fixed and variable costs for woodchips CHP in the model are taken from [33] and presented in Table 5.

<table>
<thead>
<tr>
<th>CHP</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2015-2020-2030</td>
<td>2015</td>
<td>2020</td>
</tr>
<tr>
<td>Capital costs (M$/GW)</td>
<td>4240</td>
<td>6360</td>
<td>3.959</td>
</tr>
<tr>
<td>Fixed costs M$/GW</td>
<td>30.74</td>
<td>159</td>
<td>112.9469</td>
</tr>
<tr>
<td>Variable O&amp;M (M$/PJ)</td>
<td>1.148333</td>
<td>-</td>
<td>0.00374</td>
</tr>
</tbody>
</table>

Table 5 Costs for Woodchips CHP plants [33]

Waste CHPs are also considered in the model with a production capacity of 500 KWh/ton. These plants use waste as the combustible fuel and their capacity expansion is limited due to the limited production of waste itself. Differently from biomass based CHP, waste combined heat and power offer an advantage on the combustible fuel, waste, which has an exceptionally low cost. Since the introduction of a landfill tax in 1999, energy companies started to deal with waste being paid; this increased the focus on recycling and many plants in Sweden generate electricity from waste. In 2014 a total of 2 TWh of electricity and 14.6 TWh of heat were generated to be utilised in district heating [11]. The relative costs for investment and generation are taken from [33] and then combined with the previous model (Table 6). In Figure 12 is shown an example of biomass CHP for District Heating.

<table>
<thead>
<tr>
<th>Waste to Energy CHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>Capital costs (M$/GW)</td>
</tr>
<tr>
<td>Fixed costs M$/GW</td>
</tr>
<tr>
<td>Variable O&amp;M (M$/PJ)</td>
</tr>
</tbody>
</table>

Table 6 Waste to Energy CHP costs [33]
5. District heating and heat pumps

The heating sector in Sweden is dominated by four main technologies: District heating (DH), electric heating, biofuel boilers and heat pumps [12]. The district heating accounts for more than 50% of the total Swedish demand, while 20% is accounted for heat pumps.

District heating systems provide heat for water and space heating to residential, commercial and industrial appliances. It is a safe and reliable form of heating that provides low carbon and efficient solutions. The heat can be generated from a central source or derived from a heat source and distributed through pipelines usually in the form of hot water (Figure 13).

DH heat source can be cogeneration plants, heat pumps, boilers or other forms of renewable sources such as solar or geothermal. The heat supplied through DH in Sweden is produced by different input energy such as biomass, natural gas, coal, petroleum products, electric boilers, heat pumps and waste heat [34].

Heat pumps, on their side, are highly energy efficient devices. They can provide from three to six units of useful thermal energy for each unit of energy consumed in comparison to other conventional devices for heat production that gives less than a single unit [28]. In the present model the calculations are made for an assumed COP for heat pumps of 4, where the COP is the coefficient of performance and expresses the ratio between the useful heat supplied and the work required by the system for its activity.
The heating demand considered in the model is considered as 70% of the total as a combination of district heating and heat pumps; those systems use mainly biomass and electricity to work and therefore influence the way and the amount electricity is generated. The remaining share is already taken into consideration in the total electricity demand, as it mainly consists of electrical devices. The costs for the specific technologies for heating are listed in Table 7; data for woodchips boiler and electric boiler are taken from Energistyrelsen [36] and heat pumps from IEA-ETSAP [28].

<table>
<thead>
<tr>
<th>HEATING</th>
<th>Bio Boiler</th>
<th>Electric Boiler</th>
<th>Heat Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs (M$/GW)</td>
<td>530</td>
<td>74.2</td>
<td>3000</td>
</tr>
<tr>
<td>Variable O&amp;M (M$/PJ)</td>
<td>1.59</td>
<td>0.1472222222</td>
<td>-</td>
</tr>
<tr>
<td>Fixed O&amp;M (M$/GW)</td>
<td>-</td>
<td>1.166</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7 Heating Technologies Costs [36], [28]

6. Nuclear

Nuclear electricity generation (Figure 14) takes the biggest share of electricity generation after hydro. The impact on the environment is minimal but the risk of accident is enormous. Furthermore, after a plant is decommissioned, it still needs to be cooled down. Nuclear plants in Sweden are used for the baseload; those plants have high capital costs and low fuel costs which makes them operate at a maximised level during the year.
Most of the reactors nowadays are fuelled by uranium; the plant works with turbines driven by the steam produced with the energy generated by fission \([11]\). In Sweden the policy for nuclear power includes a tax discriminating this power generation, about one third of the operating cost of the plant \([37]\). Nowadays Sweden has nine operating reactors which generates about a third of the total electricity and all of them are going to be phased out by 2045. The nuclear residual capacity considered in OSeMOSYS is as presented in Figure 15 with details on the specific reactors that are going to be turned off by the relative year.

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Operator (a)</th>
<th>Type</th>
<th>MWe net</th>
<th>Commercial operation</th>
<th>Intended decommissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oskarshamn 1</td>
<td>OKG</td>
<td>BWR</td>
<td>473</td>
<td>1972</td>
<td>2017</td>
</tr>
<tr>
<td>Oskarshamn 2</td>
<td>OKG</td>
<td>BWR</td>
<td>638</td>
<td>1974</td>
<td>Closed in 2015</td>
</tr>
<tr>
<td>Oskarshamn 3</td>
<td>OKG</td>
<td>BWR</td>
<td>1400</td>
<td>1985</td>
<td>2035 or 2045</td>
</tr>
<tr>
<td>Ringhals 1</td>
<td>Vattenfall</td>
<td>BWR</td>
<td>878</td>
<td>1976</td>
<td>2020</td>
</tr>
<tr>
<td>Ringhals 2</td>
<td>Vattenfall</td>
<td>PWR</td>
<td>807</td>
<td>1975</td>
<td>2019</td>
</tr>
<tr>
<td>Ringhals 3</td>
<td>Vattenfall</td>
<td>PWR</td>
<td>1062</td>
<td>1981</td>
<td>2041</td>
</tr>
<tr>
<td>Ringhals 4</td>
<td>Vattenfall</td>
<td>PWR</td>
<td>938</td>
<td>1983</td>
<td>2043</td>
</tr>
<tr>
<td>Forsmark 1</td>
<td>Vattenfall</td>
<td>BWR</td>
<td>984</td>
<td>1980</td>
<td>2040</td>
</tr>
<tr>
<td>Forsmark 2</td>
<td>Vattenfall</td>
<td>BWR</td>
<td>1120</td>
<td>1981</td>
<td>2041</td>
</tr>
<tr>
<td>Forsmark 3</td>
<td>Vattenfall</td>
<td>BWR</td>
<td>1187</td>
<td>1985</td>
<td>2045</td>
</tr>
<tr>
<td>Total (9) without Oskarshamn 2</td>
<td></td>
<td></td>
<td>8849</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2.1 Scenarios

Five scenarios are investigated, elected on the basis of political statements, targets and goals: Cost Optimal, Solar Empowered, Nuclear Prolonged, Comparison 13 TWh solar, Comparison solar as now.

The importance of simulating a number of different scenarios is led by the level of uncertainty that an electricity supply development can have. When a few options are investigated, a number of variables that have an impact on the decision making process are analysed in order to give the best outcome. What is common to all the scenarios is the hydropower which is fixed to a generation of 60 TWh since there are no plans for technology extension. The results obtained are compared to historical data for power generation for Sweden, then the model is run again with a limit on wind installations.

- The first scenario meets the goal of having 100% renewable generation in 2040 [21] on a “free” basis without any constraints on power.

- The second scenario takes into consideration the goal of the Swedish Solar Energy of reaching 13 TWh of electricity generation from solar [38]; the limit is set by the year 2030 and then solar is fixed to generate that amount.

- The third scenario is based on the uncertainty whether nuclear power plants, although non renewable, are going to be working until the year 2045. Then a new limit for nuclear generation is set and all the other technologies will adapt. The limit for wind power is here restricted on the basis of the maximum hours of overproduction calculated with the calculation file; this is set to 10.3 GW and 334 hours of excess in generation with no trading.

- The fourth scenario comes from as a comparison between scenario 2 and historical data for electricity generation. A new limit for wind generation is inserted in the model based on targeted maximum hours of electricity overproduction when wind and solar generation exceed at the same time. The limit for wind power capacity is set to 10 GW.

- At last the fifth scenario comes from a limitation in wind power to 10.3 GW for 334 hours of overproduction assuming the solar power to be as nowadays level.
4. Results and Discussion

The results of the different scenarios are presented and discussed in this chapter. A comparison is then made with historical data for 2015. The results indicated are divided respectively for the electricity and heating sectors which are mutually correlated.

4.1 Scenario 1

This scenario depicts the future electricity and heating system and their cost-optimal way toward a 100% renewable system starting from the year 2040. The results will be shown for the total annual generation in TWh and total annual capacity in GW both for electricity and heating. The reference year for the calculations is 2015 with its electricity demand (in blue) and generation (in red) presented in Figure 16.

![Electricity Demand and Generation 2015](image)

**Figure 16 Electricity Supply and Demand year 2015**

In Figure 17 and Figure 18 are presented respectively the total annual electricity generation and heat output. As shown in the picture the fuels used include waste, wind, solar, nuclear, natural gas, hydro, oil, coal and biomass. Electricity storage is also taken into consideration but it is not displayed as an option choosen since nowadays it is still expensive in comparison to other technologies.

The results from this analysis show that the electricity sector would gradually be dominated by wind power. In fact, wind power generation is steadily increasing and takes the role as main substitute to nuclear power, after its disclosure in 2040, along with biomass. It is evident how the phasing out of nuclear creates a rapid step down in the electricity generation in 2040, while other technologies take time to adapt.
Wind power, with its technical development, goes from a generation of 14.5 TWh in 2015 to 68 TWh in 2050. The electricity generation from wind in Sweden is led by large onshore plants while offshore wind gradually declines as it is not yet profitable and still expensive. No more solar is added since this technology does not look profitable and attractive in Sweden. Very little sun is available during winter times when the days are shorter while the electricity demand is higher. On the other side, more sun is available during summer, as the days are longer, while the electricity demand is almost halved.

Hydropower remains constant with its 60 TWh as there are no plans for extension but implementation and renovation of already existing plants [29]; the aim is to maintain the production capacity of hydropower and its balancing capacity for the electricity grid.

Waste electricity generation will stick to 3.56 TWh from year 2040, due to the limited production of waste, while biomass woodchips plants peak with an electricity generation of 41.4 TWh in 2040 to sustain the lack of nuclear and then slowly decrease to 26.4 TWh when wind stabilizes its generation.

In this configuration, the heating market will be dominated by biomass and heat pumps since electricity is getting cheaper and led by wind. Heat pumps are preferred over other electrical devices because of their higher efficiency. Electrical boilers drop to zero in the year 2040, because of the turning off of nuclear plants and hence electricity is “saved” for other purposes. Waste is fluctuating and gets to zero between years 2019-2020 when electricity generation raises and therefore the excess can be used to drive electricity driven technologies.
Figure 18 Total Annual Heat Output - Scenario 1

Figure 19 and Figure 20 display the electricity and heating capacity that this configuration follows. The year 2040 has a sudden increase of investments as it is the turning point year; nevertheless it is not realistic to have such a rapid rate of investments in the same year but those would eventually and gradually be spread around that year in the reality. Most of the capacity is taken by wind for the electricity side, sustained by biomass plants installations for up to an extra 15 TWh of generation when wind is not blowing. In the heating market, biomass is still dominating but leaving some space to heat pumps in the latest years when electricity generation becomes cheaper due to wind power increase.

Figure 21 shows how leaving wind unconstrained and free to grow up to 17.5 GW does not lead to a feasible solution; scaling up wind pattern generation from year 2015 will lead to an excess of
electricity generation for 2723 hours in the year, a share of 32%. The red circles highlight the periods when the electricity is exceeding with the highest difference between supply and demand. On the other hand, there will be periods when the gap between supply and demand is large because wind is not generating and the electricity supply has to be filled by other technologies more stable.

Figure 21 Wind and Solar Electricity Generation from 2015 scaled up to the value obtained in the model

4.2 Scenario 2

This section of the chapter presents the results for the solar empowered scenario and its annual generation and capacity; in Figure 22 and Figure 23 the annual generation is reported respectively for electricity and heating.

Figure 22 Total Annual Electricity Generation - Scenario 2

The main characteristic of this scenario is the targeted solar generation set to 13 TWh starting from year 2030 [38]. This means constantly increasing sun power capacity until ca 100 times from nowadays level, even though this is very unlikely to happen. The opposite happens with wind; data
shows the big influence that wind keeps in the total generation reaching 68 TWh in 2053 from an initial value of 14.5 TWh in 2015. This technology has been growing a lot in the past recent years surpassing Denmark and will keep this trend. Wind, in comparison to solar, is very productive in Sweden since most of its generation is achieved during winter times, when the wind blows stronger, and the electricity demand increases. Most of the electricity from wind comes from onshore technologies as the offshore technologies still remain expensive and non competitive on the market. Hydropower does not change from the other scenarios and it is kept at a constant generation of 60 TWh.

Biomass along with wind has a main role in the transition. The need of substituting nuclear power is also converged into this renewable source since it is very versatile and available in Sweden. Biomass based plants used for electricity generation have a peak of 36.2 TWh production units in the year 2040 when nuclear plants are shut down and later goes down to 24.8 TWh giving space to wind power. The rest is generated using waste plants which amounts to a stabilised level of 3.56 TWh from 2040.

![Figure 23 Total Annual Heat Output - Scenario 2](image)

Figure 23 shows the heat output for this scenario. Most of the heat is generated through technologies fuelled with biomass with a 60.8 TWh peak between the years 2040 and 2043. Waste is also harnessed to the limit following the availability of waste produced, while the heat generation through heat pumps slightly decrease from 27.3 TWh in 2015 to a minimum of 13.5 TWh in 2034 and later increases again to up 28 TWh in 2054 depending on the availability of cheap electricity. Electric boilers follow the same pattern with a peak of 20 TWh in 2034.
It is interesting to note how biomass is essential in the transition to a low carbon economy, especially for heating purposes. Sweden is rich in biomass and its cost is very competitive in comparison to other Countries, where the price can be doubled.

On the capacity side, shown in Figure 24 and Figure 25 respectively for electricity and heat, the cumulative installations are presented.

As the electricity generation will be mainly driven by wind and biomass, the capacity of these technologies has to grow. The peak of installments is verified between the years 2038-2040 as the nuclear is being phased out and the other technologies have to follow the “gap”. Wind is rapidly growing without any constriction from an initial capacity of 6.52 GW in 2015 reaching 17.5 GW in 2053. Biomass peaks in the year 2040 with 12.65 GW of installed capacity, maintaining the same until 2060. As well as for the production, the capacity of hydropower remains constant at 17.2 GW.

Figure 26 shows how many hours generation exceeds demand in this configuration; the hours when the difference is higher are highlighted with a red circle. The overproduction amounts to 3005 hours, 34.3% of the year, with a peak on the 25th of December of 13 GW of excess. On the other hand, in other periods of the year the combination of solar and wind leaves a big gap between supply and demand that has to be filled by other technologies. It is then clear how this configuration is not feasible for the system due to the intermittence of solar and wind power.
4.3 Scenario 3

This scenario assumes that nuclear power will continue working until the year 2045, when the last reactor Forsmark 3 will be turned off [37]. Wind power is set to a maximum capacity of 10.3 GW, with the help of the calculation file, limiting to 334 hours the electricity excess and its peak of 4.4 GW in december (Figure 27). The generation trend would not be exactly the same as 2015 and there might possibly be possibility of trading in some hours; hence this configuration might be feasible without affecting the system stability.

Results of the modelling for this layout are presented in Figure 28 for electricity generation. It is evident how in this scenario the electricity generation follow a smoother path compared to the previous ones, without causing a sudden change in 2040; nuclear power is decreasing more gradually and gives space to other technologies to adapt slowly. The electricity generation is also slightly falling off as the electricity previously used in the heating sector will be substituted with biomass.
By setting wind power to a maximum capacity of 10.3 GW, wind power generation amounts to a maximum of 39.7 TWh in 2048 keeping the same trend till 2060. Fundamental is the role of biomass which sees a rapid increase towards the year 2039-2040 with 12.65 GW of capacity installed to balance the lack of nuclear. Biomass plants reach their peak production of 45 TWh in 2045 continuing with 43 TWh till the end while waste electricity generation maintains its maximum of 3.56 TWh. This configuration is pretty stable since most of the electricity generation is relied on biomass which is a renewable source not fluctuating as wind or solar.

In the heating sector, biomass again keeps its central role since the heat production from CHP and biomass boiler is rapidly increasing reaching a share of 93% with 73.11 TWh from 2047. The rest is
generated with heat pumps which slowly decreases from a maximum of 28 TWh to a minimum of 5 TWh. The installed capacity of electricity and heat power are shown in appendix A.

4.4 Scenario 4

The present section introduces the results from the comparison between scenario 2 and historical data. The limitations for this scenario are based on the assumption that a base load of hydropower and electricity from industrial CHP will be anyway generated and assumed to be 4500 MW [24]. The rest of the demand needs to be satisfied by other existing technologies.

In this scenario wind power generation from 2015 has been scaled up to the maximum value for wind installations obtained with the model in scenario 2, taking into consideration the improvement of the capacity factor of 60% on average. The same as been done with solar installations, scaling up its reference production to the GW of installations obtained in the model to reach the targeted value of 13 TWh of power generation (Figure 30).

Given these considerations, a limit for wind power is set to 10 GW while solar is fixed to 10.8 GW as output capacity from the model when the annual production is 13 TWh. The combination of wind and solar in this configuration would give 387 hours of excess between electricity supply and demand, a share of 4.4 % of the whole year (Figure 31) with a peak of 4 GW excess in July; with these values the arrangement might be feasible.
Figure 31 Wind and Solar Generation Scaled up from 2015 to the value obtained by the model - Scenario 4

The total annual electricity and heating generation are presented in Figure 32 and Figure 33. In this configuration solar power is maintained to 13 TWh as targeted from the Swedish Solar Energy, even though it is quite difficult to reach from nowadays level and the low presence of sun.

Nuclear phase-out creates again a sudden step down in the electricity generation in 2040. Wind power reaches its maximum generation of 38 TWh from year 2048 until the end. Biomass peaks in the year 2040 with 38.2 TWh of electricity generation and maintains its level to 33-34 TWh for the upcoming years.

Figure 32 Total Annual Electricity Generation - Scenario 4

Eventually most of the heat will be generated almost exclusively using biomass based technologies and woodchips CHP plants amounting to ca 83%, while the remaining would be generated through heat pumps. Less electricity devices will be used in this configuration as wind power generation is limited. Waste plants stop working in the middle years as soon as they become old and no more investments are done since they run on bigger costs than other technologies.
The capacity for the different technologies is shown in Appendix B. There will be an additional capacity for biomass plants able to generate up to an additional 4-5 TWh of electricity when other renewable intermittent sources are not available.

### 4.5 Scenario 5

This section depicts the scenario when solar power is not expected to grow, as a result from the model, while the wind is fixed at a maximum level; the level is set to 10.3 GW with an excess between demand and supply of 334 hours (Figure 34) and its peak of 4.4 GW in December. The limitation of wind power in this scenario is the same as for scenario 3, but the difference is that nuclear power for this scenario is phased out in 2040 and the remaining technologies will adapt accordingly.
The electricity generation and heat output will follow in Figure 35 and Figure 36. In this configuration, biomass after hydropower is the main responsible of electricity generation reaching its peak of 50 TWh in 2040, end year of nuclear power; this value is the maximum among the all scenarios and makes evident the dependence on biomass when solar is not productive and wind has to be limited because of its intermittence. Wind generation has its peak of 39.7 TWh from 2046 until the end.

The heating sector is dominated by biomass which reaches its maximum generation value of 73 TWh among all the scenarios. Around 92-93% of the total heating demand will be satisfied by biomass driven technologies while the remaining part goes to heat pumps.
4.6 Emissions

In this section CO₂ emissions are presented as a comparison between the different scenarios previously discussed. Figure 37 shows that emissions tend to increase and have a peak between years 2017-2019 when the electricity generation is higher because electricity is used to run electrical devices for heating purposes. In the following years a rapid decrease of emissions is displayed followed by a stabilisation due to the adaptation of new renewable technologies and a decrease in electricity generation that is only generated to satisfy the internal demand. Scenario 4 is the one with the highest emissions while Scenario 3 emits the least; this is mainly due to highly CO₂ emitters technologies, such as those driven by heavy fuel oil, that are differently harnessed as a consequence of the adaptation of renewables progresses. The emissions for biomass based technologies are calculated to be zero with the assumption that trees are replanted to take up the CO₂ released in the atmosphere when the trees that have been removed are burnt to generate electricity.

![Emissions Comparison](image)

**Figure 37 Emissions - Comparison between scenarios**

4.7 Costs

The investment costs for a fully renewable system has been annualized with the purpose to present the costs to be spread in the years and not as if the whole investment would be sustained all at once (Figure 38).

The comparison between the different scenarios show how the investments costs differs from each one; the most costly are those scenarios where solar power is forced to grow and increase its
capacity around 100 times from nowadays levels, even though this technology is not profitable in Sweden. The less costly, on the other hand, are the scenarios where nuclear is prolonged until 2045 and the solar is not growing but remains at the same level as nowadays; therefore less investments are required.

The peak for the Annualized Investment Cost among all scenarios amounts to a maximum of 3884.26 M$ in 2041 for the solar empowered scenario; this is mainly caused by the installation of technologies to sustain the upcoming lack of nuclear and turning off of reactors by 2040 together with high investments in solar power. On the other hand the peak for the Nuclear scenario is in 2045, year where the last nuclear reactor is turned off.

![Annualized Investment Cost](image)

**Figure 38 Annualized Investment Costs**

*Fixed and Variable Operation and Maintenance (O&P) costs are calculated and presented in this section, combined with the Annualized Investments and Emissions Costs to determine the yearly Electricity Generation Cost.* The cost for emissions has been assumed to be 16.54 $ per tonne up to an increasing value of 23.15 $ from 2030 and 39.7 $ from 2050 [39]. Fixed and variable costs for those technologies such as CHP, generating both electricity and heat, are multiplied by the relative efficiency of the plant in the electricity generation. The calculation used to determine the electricity generation cost (EGC) is as follows:

\[
EGC = \frac{(\text{Annual Investment Cost} + \text{Fuel Cost} + \text{Fixed O&M} + \text{Variable O&M} + \text{CO}_2 \text{ emissions Cost})}{\text{Electricity Generated}}
\]
The electricity generation cost (Figure 39) fluctuates between a value of 0.013-0.015 $/kWh in the first years to a maximum value of 0.05 $/kWh in 2040, turning point year. The cost to generate electricity steadily increases with time. The rapid peak observed between years 2038-2041 is due to the rapid investments rate that has to be faced in those years to switch to a fully renewable electricity generation compensating the sudden lack of nuclear. For this reason the Nuclear scenario is the one that is affected the least by the costs change; in this scenario nuclear plants are running until year 2045, hence this gives time to other technologies to adapt. Also, the electricity generation suddenly decreases in 2040, making the denominator in the equation smaller and therefore driving immediately the EGC up.

The solar empowered Scenario, on the other hand, is the one that is affected the most since the solar power capacity has to be scaled up to ca 100 times and hence more investments have to be done. It is important to note that in order to reach a fully renewable electricity system, the price of electricity in the market might be more than doubled in the upcoming years as a consequence of the costs increase. This might also lead to a change in the electricity demand and supply patterns.

Figure 39 Electricity Generation Cost
5 Conclusions

The Swedish energy system can count on a high variety of renewable sources and Sweden is recognized as one of the leading country among the IEA members; with its high share of renewables in the electricity generation at the present time Sweden has all that it takes to develop a 100% renewable electricity system. Results from the modelling presented that the cost optimal option is identified in large scale wind power, due to the high presence of wind in the winter times when the electricity demand is higher. The reliability on wind energy though cannot be supported to a limitless extent, since the fluctuations of the wind can drive the electricity generation too high or too low; the graphs demand-generation scaled up show the intermittence of wind generation. For this reason wind power has to be limited and supported by other more stable technologies than can generate energy when it is demanded. Solar technologies are not preferred as only a few sunny days are found in summer, where the electricity demand is low. The optimal option for Sweden is then identified in biomass; the large amount of wood in Sweden is enough to give this source a fundamental role in the energy system. Biomass energy does not have to deal with natural fluctuation, as for sun or wind, and can easily be stored in solid form representing the optimal compromise between system reliability and stability.

Even though the fully renewable path is theoretically feasible, some challenges need to be addressed on the financial and technical side. The investments for a 100% RE electricity system have their peak around the year 2040, driving the electricity generation cost up to almost three times the current cost. This will have a direct influence on the electricity price for the customers and might change their demand. It is also true that Energy efficiency measures are growing and might lead to a decrease of the electricity demand, with a consequent decrease of GW of new RE technologies to be installed. Potentially Nuclear can be left running until year 2045 as this can lower the electricity costs and make the transition smoother.

The current study presents both strength and weaknesses; it provides an optimal solution on the financial side along with the technical for many years to come, but the time slices are limited and grouped to several hours per month. Later studies could analyse the electricity generation on a hourly basis, individualizing the difficulties in the transition from one technology to another for demand and supply to be met every hour. Results also show that biomass could lead the heating market after 2040 while supporting wind electricity generation in the electricity sector; suggestions
can be analysing the biomass evolution in the transport sector as well. These two cases can be better studied and will be left for further research.

6 References


Appendix A

Figura 40 Total Annual Electricity Capacity - Scenario 3

Figura 41 Total Annual Heat Capacity - Scenario 3
Appendix B

**Figura 42** Total Annual Electricity Capacity - Scenario 4

**Figura 43** Total Annual Heat Capacity – Scenario 4