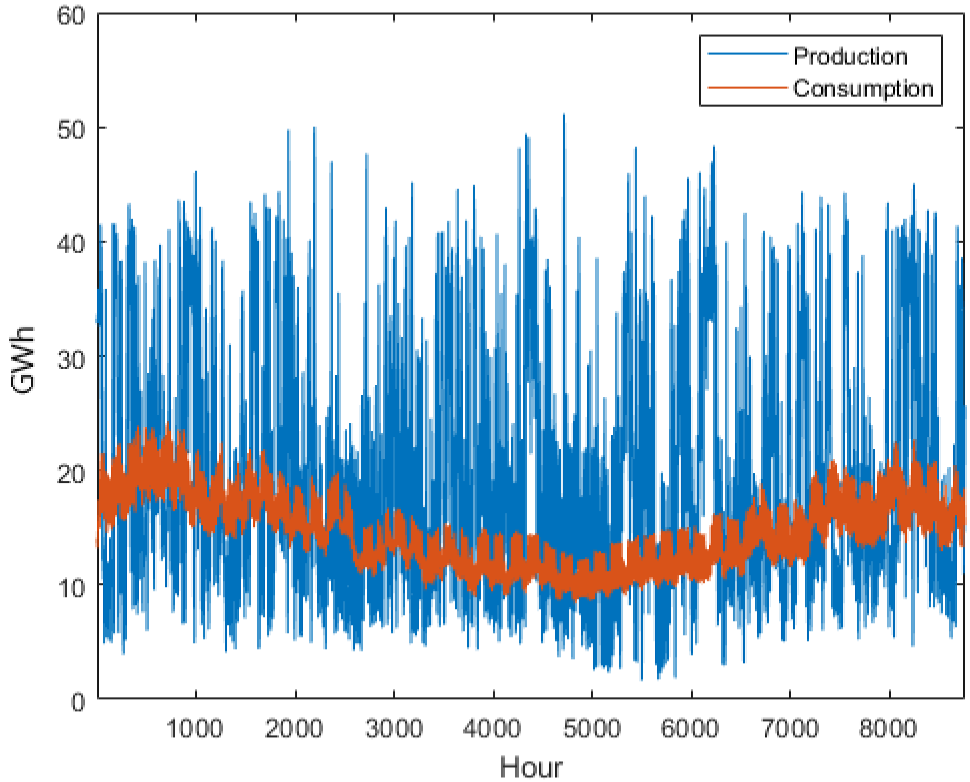

Scenario analysis of renewable energy integration

An investigation of a grid composition of hydro, solar, wind and storage in future scenarios

Master's thesis in Industrial Ecology

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Abstract

This thesis deals with the construction, implementation and simulation of a Matlab program for a renewable energy system. The primary aim with the thesis was to calculate the total cost for a system consisting of wind, solar and hydropower complemented with a storage system of lithium-ion batteries and hydrogen. Four cases have been evaluated based on the weather conditions from 3 different regions in Sweden.

Implementing a hydrogen storage system reduces the cost compared to a battery storage system. However, the battery storage system has a better stability of the system frequency in comparison to a hydrogen storage system. As a result, the battery storage system would require less ancillary services designated to the stabilization of the system frequency which would be an additionally cost to the hydrogen storage implementation cost. Additionally, having a base load power plant in the form of hydropower that can provide stable power output will reduce the need for overgeneration and consequently larger storage system due to the intermittent nature of wind and solar.

Keywords: renewable energy, utility scale storage, grid composition, lithium-ion batteries, hydrogen, wind turbines, solar PV.

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Patrik Nilsson & Alexander Munge
Gothenburg, June 2020

Contents

1 Introduction

1.1 Background

Since the industrial revolution in the 18th century, there has been an increased usage of fossil fuels mainly within the areas of transportation, generation of electricity and heating[1]. During the 19th century, the Swedish physicist Svante Arrhenius discovered the correlation between emissions from CO_2 and the greenhouse effect that is heating up planet Earth[2]. Since then, the problems have become more serious as the emissions from the most contributing greenhouse gas CO_2 have continued to increase and as of today, there have been significant changes in the climate as the Keeling Curve indicates an average monthly CO_2 level in the atmosphere now exceeding 400 ppm, up from a level of 315 ppm from when the measurements started in 1958. The pre industrial level of CO_2 in the atmosphere was under 300 ppm[1].

The 2015 UNFCCC Paris Agreement states that the temperature increase on Earth must be kept to a maximum of 1.5 degrees Celsius above pre industrial levels. The European Union have set up a framework where the emissions at a first step by 2030 should be reduced by 32% compared to the levels of year 1990.

Technologies such as solar PV and wind power have become more efficient and cheaper during the last decades meaning that they have become cost competitive compared to other technologies using fossil fuels. Investments in renewable technologies have increased and they are now driving down the cost for electricity meaning that old coal fired power plants can not produce at the same low cost as new and clean technologies, meaning that the incentive for shutting them down has increased[3]. However, with increased integration of renewable energy technology, the need for utility-scaled storage systems is increased. Research and development into energy storage systems has led to new possibilities and it is now possible to store large amounts of energy in lithium ion batteries and hydrogen to use fuel cells.

1.2 Previous Work

The previous work conducted to investigate future scenarios of the transformation of Sweden's energy mix to a more renewable mix has primarily been focusing on the expansion of wind and solar, as replacement to the decommissioning nuclear plants. Estimations regarding costs of such systems vary and depends on several factors, such as the geographic boundaries of the study, the storage technology implementation and the assumptions based on weather conditions.

Kan et al. (2020) made a simulation of an electricity system without nuclear power in Sweden. The optimization tool used is a greenfield capacity expansion model named REX with a time horizon in the simulation to 2045. In order to be able to adjust the supply and demand via export and import of electricity, the system boundaries is an interconnected energy system in Europe with the main focus on Sweden. The emission constraint for generation, transmission, storage and demand-response is set to 10g/kWh, corresponding to a 98% reduction in emission compared to the level of 1990 for Europe. The result shows an average system cost of 46-61 USD/MWh[4].

In a study by the Swedish consultancy firm Sweco, Krönert et al. investigated two scenarios for an energy system consisting of 100% renewable energy in Sweden by 2050. Scenario 1 has a main focus on onshore windmills being built in the northern parts of Sweden with an annual production of 75 TWh combined with 10 TWh from solar PV. In order to handle the peak loads, hydro power stations will be expanded by 25%. In scenario 2, onshore and offshore windmills with an annual production of 55 TWh are combined with solar PV in the southern parts of Sweden corresponding to an annual production of 20 TWh. The power from hydro will not be expanded. In order to handle peak loads, a capacity of 5500 MW of gas turbines will be installed. The result for scenario 1 shows total investments of 1554 billion SEK up to the year 2050. In this sum, reinvestments in the grid and energy storage is included. For scenario 2, the result shows a total investment of 1638 billion SEK, reinvestments in the grid and energy storage included[5].

Fischer et al. (2020) investigated a case with an optimal sustainable energy system in the Nordic municipalities. For the case study, Piteå municipality with 42 000 inhabitants(2015) was used as a representative municipality. The simulation program EnergyPLAN was used together with an multi-objective evolutionary algorithm that were implemented into Matlab. The aim with the study was to identify alternatives for an increased share of renewables in the local energy system within the time span up to 2030. The simulations were performed as hourly simulations over a year. The technology cost of the year 2015 and the Nordic electricity system with an average price of 40 EUR/MWh and a discount rate of 9% was the basic scenario for the study. This gave a total cost of 81.9 million EUR. For another scenario, the fossil fuel technologies were converted into renewable heating consisting of biomass and heat pump solutions together with the implementation of energy efficiency measures in the building sector and the technology cost for year 2020 gave a total cost of 78.1 million EUR[6].

1.3 Purpose statement

The purpose of this report is to investigate the cost of having an energy mix based on renewable energy sources of hydro, solar, wind and storage consisting of lithium-ion batteries and hydrogen in a constructed future scenario. The total cost will be determined by analysing the cost of the system components, the size of the storage system and the allocation and balance of the load and generators. Additionally, the environmental impact from the system will be analysed. The analysis will be based on current data from Sweden's energy system. It is assumed that the grid can transport electricity and that the distribution works.

2

Theory

This chapter aims to provide relevant theory to provide a basis for understanding and interpretation of the project results.

2.1 Grid balance

According to AZoM (2016), grid balancing is described as the act of matching the supply of electricity with the demand by utility companies. It is essential that the balance between total production and total consumption is maintained in order to maintain a stable system frequency [7]. With the absence of balance, the quality and stability of the power will subsequently deteriorate and may lead to the disconnection of system components. The resulting scenario from disconnecting components will result in blackouts[7]. As the market share of renewable energy technologies increases, maintaining the balance in the system provides a challenge as the weather affects both production and consumption[8]. Due to this phenomena, renewable energies often supply either too little or too much electricity to the grid, which needs to be balanced in order to minimise the risk of damaging electronic components in the system[8].

There are several strategies to balance the grid. The bulk balancing is made through ramping up the power generation of the existing infrastructure depending on the flexibility of the technology[8]. In order to determine which plants that is ideal to use during the day, grid operators would utilise the method of merit order in order to rank the power plants based on the lowest cost alternative[9]. These are separated into base-, mid- and peak load. Technologies such as nuclear plants, which is characterised by having low running costs, is often a base load plant which operates continuously throughout the year. Base load plants are designed to supply a steady output of power generation and are thus not ideal for rapid responses in emergency situations or scaleable for peak demands[10].

The demand varies throughout the day and year but will maintain a base demand that is covered by the base power plants. At certain times, such as during business hours, the demand increases. The demand that exceeds the base level is covered by mid load plants (often characterised by coal and lignite plants) and during peak hours additional generation is supplied by peak power plants (often characterised by natural gas or pumped storage)[9][10].

When the market is increasingly comprised of renewable energy, challenges face the traditional merit order system. Since solar and wind power is intermittent, grid operators must ensure the utilization of these technologies when they have the ability to produce electricity. Since grid operators do not have the same control of adjusting the supply of electricity when relying on renewables with the same flexibility as the traditional generation technologies, alternative methods of grid balancing must be incorporated in balancing the supply and demand of electricity[9]. One such solution is incorporating an effective storage system which can be used during peak demands and utilised with immediate action. This will help to mitigate the negative effects of becoming more reliant on intermittent technologies[10].

2.1.1 Intermittency

Intermittency occurs in several areas within the energy sector, such as solar radiation, wind and load. Intermittency includes various timescales which needs to be accounted for, including hourly changes, diurnal and variations between seasons[11]. The significance of intermittency is apparent when developing strategies for power generation, as it is necessary to ensure balance between supply and load in a grid composition[11]. Rowe, D. et al. (2016) measured data from a residential house in Australia and depicted the variation in energy consumption during the course of a 24-hour period. They found that there were patterns in the variation of consumption in the residential household over the course of a year and the correlation of the consumption with the aggregated consumption of the community. According to Rowe, D. et al. (2016) it is imperative for additional technologies to safeguard the continuous balance of supply and load due to the intermittent nature of renewable energy technologies. A grid system solely comprised of renewable energy must have utility-scale storage systems in place[11]. However, it is not possible to have a grid system that always works as it is supposed to since unknown events in production and consumption will always occur. Examples of this includes a large and sudden increase in demand resulting in a frequency drop that is hard to regulate, resulting in potential blackout within the system if not loads are being disconnected [12].

2.2 Wind energy

The concept of the Gedser wind turbines was developed by Johannes Juul in the 50's and came to use for large scale production of electricity in the 80's. Wind energy is converted into rotational energy and is transformed into electrical power via the generator. Wind turbines can be divided into two categories, onshore and offshore. Offshore wind turbines are ideally built nearby the coast within a distance of 100 km. In order to make it economically feasible, they must be built at shallow waters, i.e. a depth of up to 40 meters. One advantage with the offshore sites is that the energy yield is higher than for the onshore sites. One of the disadvantages is that the sites are at remote areas so maintenance will be more expensive[13]. The maximum theoretical power output from a wind turbine is given by the following equation according to Betz law that states

$$\frac{1}{2}\rho A V^3 C_p \tag{2.1}$$

ρ= density of air $[kg/m^3]$
A= cross sectional area of the turbine blades $[m^2]$
V= air velocity[m/s]
C_p = the efficiency of the turbine, where 59.3 % is the maximum theoretical efficiency according to Betz law.

The wind turbines have a technical lifespan of 20-25 years. From a life cycle perspective, about 84% of the total energy use originates from the manufacturing process, 7% from transport, 4% from maintenance, 3% from dismantling and 1% from running. The carbon footprint from onshore wind turbines are 20-38g CO_2/kWh while the offshore turbines gives a footprint of 9-13g CO_2/kWh[14]. The recycling of the wind turbines can be done using separation of the different material fractions. However, the wind turbine blades are made from composite materials which means that they are difficult to recycle. Currently, the materials are separated using mechanical crushing but this method has a disadvantage due to the formation of poisonous dust. Another way the separation can be done is by using incineration but the energy gain is low and it will be a lot of waste product left afterwards. Lastly, chemical separation can be used but this method requires chemicals that are expensive and hazardous[14].

2.2.1 Wind profile/wind conditions

The wind profile gives information about the horizontal wind conditions at different heights. At higher altitudes, the wind velocity is higher. The wind profile varies with the topography. Barriers in the area such as a forest will increase the turbulence and this will require the hubs to be built higher in order to decrease the stress on the construction[53]. The AEP (Annual Energy Production) curve describes the annual production of energy as a function of the average annual wind speed [m/s]. In order to maximize the annual production of electricity, an optimal size of the rotor blades has to be chosen in relation to the wind conditions at the site[15].

2.3 Learning curve

The learning curve describes the rate of learning how to produce or construct something more efficient as one gets more experience. Early in the life cycle of a product, the market is a small niche with low production volumes and few customers that are willing to pay a high price for the product. In this phase, improvements yield a high return. This phase is followed by the growth phase where the product enters new markets, competitors may enter the market by learning by imitating, the production volumes starts to grow and the organizations learn how to scale up production (economies of scale) in order to increase its productivity. It can also be the case that the organizations learn by employees changing between the companies, taking their knowledge with them. The product price falls. Lastly, the product enters the maturity phase with a slower growth on the market and diminishing return on improvements. The learning here consists of, among others, consecutive mass productions with improvements, for example automation of the factory. It is the total accumulated experience from development and production that increases the knowledge. The learning curve can be described via the relation

$$y = ax^{-b} \tag{2.2}$$

y= unit labor requirement
a= the labor requirement
b= parameter for measuring the extent of learning

The graphical expression is an exponential decay function where the cost per produced product decreases exponentially with more experience as a function of the accumulated output[16].

2.4 PV

Photovoltaic (PV) technology converts solar energy to electrical energy. One such technology that is increasing its rate of implementation are PV cells. This technology allows harnessing the large amount of energy being radiated towards Earth constantly from the sun, where our civilisation would only require a minuscule fraction of the incoming solar radiation to match the energy demand [17]. Additionally, solar cells don't emit pollutants into the atmosphere during their use-phase, however the manufacturing part of their life cycle as well as the end-of-life treatment incurs certain negative environmental effects[17].

The output from solar panels can be calculated using the following expression

$$E = A\eta HPR \tag{2.3}$$

where E is the energy output from the solar panel in kWh, A represents the area of the solar panel in m^2, H is the average solar radiation (kWh/m^2), η is the efficiency of the solar panel and PR is the performance ratio.

2.4.1 Types of cells

As of 2017, the primary material used for the production of solar modules are single-crystal silicon or multigrain silicon [17]. However, a disadvantage to crystalline silicon is the requirement of thicker material due to the nature of the indirect bandgap of silicon, as opposed to direct bandgap [17]. Single crystalline silicon PV modules has a conversion efficiency of around 20 % whereas multigrain crystalline silicon has a conversion efficiency of around 17 %, however it does come with reduced cost due to the method of production [17].

Single-crystal silicon and multigrain silicon are the most efficient alternatives for single junction cells, however they are not the most efficient solar cells purely based on performance [17]. The more efficient, albeit more expensive, alternative is a GaAs multijunction solar cell on Ge substrates that yields an efficiency of 38 %. Currently they are primarily used and implemented in space as conventional solar panels are not durable enough for the extreme conditions encountered in space [20]. According to Kasap & Capper (2017), the main issue that is inherent with large-scale implementation of solar cells is the integration with buildings, as the area on rooftops are often ideal to use.

2.5 Fuel cells

The utilisation of hydrogen fuel cells and storage is an emerging concept within the energy sector for utility-scale energy storage and subsequent conversion. The main components of such a system are an electrolyser, hydrogen storage tank and fuel cells [19]. The electrolyser uses electricity to fuel the generation of hydrogen through splitting water molecules into hydrogen and oxygen. In a system consisting of a large share of renewable energy sources, the excess production of electricity during certain time frames can be used to fuel the electrolysers according to Kharel et al. (2018). The hydrogen is thereafter stored in storage tanks either as a gas or liquid, where storage in gas-form requires high-pressure tanks with a pressure of 350-700 bar [21]. Hydrogen storage in liquid form requires temperatures below -252.8°C as this represents the hydrogen boiling point at one atmospheric pressure [21]. Whenever the renewable energy system enters time periods of diminishing output (for instance solar panels during the winter season in Nordic countries), the stored hydrogen can be used in fuel cells to generate electricity and therefore cover the demand. According to Kharel et al. (2018), hydrogen storage is suitable for long-term energy storage due to its high power rates of 10 MW.

Rowe et al.(2016) states that there are high expectations on large price reductions within fuel cell technology as a result of the fact that utility scale solid oxide cells are undergoing significant investments in development and market introduction. Hydrogen as a fuel also has the benefit of high energy density of 120-142 MJ/kg (compared to gasoline of 44 MJ/kg) [21]. However, Rowe et al. (2016) also mention that the required infrastructure changes and investments may be a deterrent for near-future implementation in the energy system.

2.6 Lithium ion battery

A lithium ion battery consists of an electrochemical cell with two electrons and a separator. During charging, the ions in the battery are transported from the positive side via the separator to the negative side. When this happens, the electrons will pass via the external circuit generating voltage. Chemical energy has now been converted to electrical energy. The reverse will happen during use of a battery, i.e., discharging[22].

There are two types of battery cells, primary cells (non rechargeable) and secondary cells (rechargeable). The energy in a battery cell is the the maximum work that can be performed before reaching low voltage and a need for recharging. The power in the battery cell is at which rate this work can be performed. When designing a battery cell, this needs to be taken into consideration since there is a trade off between them and it is not possible to optimize both of them in the same battery cell[22].

The durability of a battery cell can be divided into two categories, the calendar life and the cycle life. The calendar life is the irreversible degradation in capacity due to storage and it is affected by storage temperature and state of charge. The cycle life is the amount of complete charges and discharges a battery can complete before the total capacity within the battery cell falls below 80%[22]. Utility scale stationary batteries can be used to store energy on short term time span, hours up to a day. When there is an excess production from renewable energy sources, the energy will be stored in the batteries. When the demand for electricity is higher than the supply, the batteries provides the grid with electricity. This means that utility scale batteries functions as a regulator for the frequency with a respond time measured in milliseconds. Batteries have the advantage of being flexible when one needs to ramp up the energy supply for a couple of hours. They can be used in a decentralized way with plants of batteries being built and connected to the grid close to areas where one can expect peak demand. This could enable better grid control due to less congestion[23].

The primary use for batteries in a grid system is to store energy on short term time span, i.e., hours up to days.

2.7 Hydro power

Hydro power has been used for several millenniums. During the 19th century, water wheels were connected to generators in order to generate electricity. The Fourneyron turbine was developed in the early 19th century and it operated at an efficiency of 80%. Later that century, other types of turbines were invented such as the Pelton turbine, the Francis turbine and the Kaplan turbine. As of today, the Pelton turbine is the most common type of turbine to use in hydro power stations. Hydro power is a renewable energy source where the potential energy are being used. The water flows through a turbine which transfers the potential energy to mechanical energy in the turbine and then to electrical power via the generator. The hydro power plants can be used for regulation and balancing of the grid during peak loads. The hydro functions as a battery where it is possible to store energy. The potential energy can be described by the formulae

$$E = mgh \tag{2.4}$$

m= the mass of the water [kg]
g= the gravitational acceleration [m/s^2]
h= the height [m]

Two of the main types of hydro power stations are the run of river hydro power stations and the dam and reservoir power stations. For the dam and reservoir power stations, a dam is required. These dams can be designed in several ways including among others, the gravity dam and the concrete arch dam. The larger the hydro power stations are, the more impact on the local environment. Examples on local impacts are that the flow may affect the sedimentary in the river and downstream water flows, including erosion . The greenhouse gas emissions from hydro power stations is 10-13 kg/MWh. On the advantage side, when hydro power stations have been constructed, they can be up and running for at least 50-100 years. Hydro power stations have a high CAPEX but the operation cost is in comparison low. As of 2016, the total installed capacity of hydro power including pumped hydro in the world accounted to 1246 GW[24] .

2.8 Cost of grid

There are several aspects to consider in terms of how a grid economy functions, however it is possible to break it down into subsections of cost and pricing. The costs associated with generating electricity can be divided into three categories: fixed, variable and quasi-fixed costs [25]. Fixed costs are typically characterised by the construction of the plant, connection to the grid, land purchasing as well as other non-variable costs. The Open Electricity Economics Handbook states that fixed costs are deemed as sunk costs due to the only nature of recuperating any portion of the fixed costs is through the potential sale of the plant or decommissioning of the plant [25].

Variable costs are on the contrary not regarded as sunk costs and are an important variable in determining which existing plant to use for the generation of electricity. Variable costs are characterised by expenditures such as fuel costs, operation and maintenance and, depending on the politics of the region, costs associated with environmental degradation [25]. The third category of expenses, quasi-fixed costs, are somewhere in between fixed costs and variable costs and is characterised by personnel expenses, however they are occasionally incorporated into variable costs if the magnitude of the expense is small enough to disdain from a separate category [25]. The difference between the magnitude of fixed costs and variable costs vary greatly depending on which plant, where renewables usually have close to zero variable costs whereas fossil fuel plants have a large portion of their total costs allocated to variable costs [25]. This is one of the primary reasons to using power plants such as gas-fired combined cycle plant to cover peak load in order to minimise the variable cost of the plant.

2.8.1 Annualized fixed costs

The fixed costs that were invested can be translated into annualized costs to analyze the investment cost spread out over the course of the technical lifetime of the plant [25]. This help get a better understanding and a more accurate comparison between the fixed costs of a power plant. The annualised fixed cost (AFC) can be calculated according to the following formula

$$AFC = \frac{C_{fix} r(1+r)^T}{(1+r)^T - 1} \tag{2.5}$$

where the resulting AFC is measured in $\frac{SEK}{kW \cdot year}$, C_{fix} is the fixed costs and measured in $\frac{SEK}{kW}$, r is the discount rate and T is the corresponding technical lifetime in years.

2.8.2 Levelized Cost Of Electricity

The levelized cost of electricity (LCOE) can be described as the aggregated discounted lifetime cost of generating electricity. This help to use as a basis of comparison for the cost of generating electricity between different power plants where both fixed cost and variable costs are taken into account [25]. The LCOE is calculated using the following expression:

$$LCOE = \frac{C_{fix} + \sum\limits_{y=1}^{Y}(1+r)^{-y}C_y}{\sum\limits_{y=1}^{Y}(1+r)^{-y}G_y} \tag{2.6}$$

where the LCOE is measured in $\frac{SEK}{MWh}$, C_{fix} represents the fixed costs, C_y is the variable costs during year y, the technical lifetime of the power plant is represented by Y, G_y is the generated electricity from the power plant in year y, and finally the weighted average cost of capital corresponds to r.

Certain issues arise when using LCOE as a metric for comparison however, especially when using it as a basis for comparison between fossil-fuel based power plants and renewable based power plants [25]. When it comes to renewables, the costs can vary greatly depending on the wind profile of the region for wind power plants, or the solar radiation for solar panels, pertaining that the levelized cost of electricity is not solely based on the technology itself but also includes the environmental factors of the location. In terms of fossil-based power plants the levelized cost of electricity can vary greatly between countries as factors such as cost of labour and taxes on environmental degradation have an impact on the LCOE metric [25].

2.9 Environmental impacts of grids

Depending on what generation technology that is used in the electricity grid, varying environmental impacts will occur. In order to quantify and assess these environmental impacts, there are several tools that can be used such as life cycle assessment and subsequently characterization indicators.

2.9.1 Life cycle assessment

Life Cycle Assessment (LCA) is used in order to get a holistic picture of the environmental impact of a product. Two of the main approaches when doing an LCA are cradle to grave and cradle to gate. In cradle to grave, the aim is to look at the whole chain from extraction of the raw materials needed for the product, manufacturing and usage of the product until recycling or disposal. In cradle to gate, the aim is to look at the extraction and production but the usage and the disposal is left out. The procedure when doing an LCA study starts with the goal and scope definition where the product and the purpose are defined. In the next step, an inventory analysis will be performed which is a flow model of the technical system, including its system boundaries. This is followed by the impact assessment where the environmental loads are being quantified. The aim here is to get more specific information about the environmental impact[27].

2.9.2 Characterization indicators

The characterization indicators are used in a quantitative way to measure the environmental impact. They can be divided into different categories, including among others, land use and global warming. Land use measures the change in how land are used, changes in biodiversity and things that supports the ecosystem. The aim is to avoid sub optimisation in the use of land, i.e. that one think it is used in a efficient way whereas it is not because problems arise in other areas. Global warming is another characterization indicator with the aim to measure how the product will affect the global warming of the planet. The global warming is measured using GWP (Global Warming Potential) [27].

2.10 Burgman equation

The Burgman equation is used for calculating the sensitivity in a specific parameter using the following expression

$$S = \frac{\frac{\Delta y}{y1}}{\frac{\Delta x}{x1}} = \frac{\frac{y2-y1}{y1}}{\frac{x2-x1}{x1}} \tag{2.7}$$

Where S= the sensitivity A value >1 indicates that there is a sensitivity, a value close to 0 indicates that there is no sensitivity and a value of exactly 1 indicates proportional. Positive and negative numbers are all treated as absolute values[29].

3
Methodology

3.1 Research Method

The questions to be answered in this thesis are what a renewable energy system based on weather conditions in Sweden would look like, what environmental impact it would have during the life cycle and how much it would cost. In order to answer those questions, the thesis work will be performed using a quantitative research method. The data collection for this thesis will be conducted by reading scientific reports, articles and books. This data will then be used to make assumptions for the different chosen parameters used in this thesis. These parameters will then be implemented into different cases under chapter four in the thesis. The data from the cases will then be implemented in a created Matlab program where simulations will be run. An analysis of these simulations will then be conducted, linked to the aim of this thesis. This is followed by an sensitivity analysis using Burgmans equation where the parameters will be evaluated if they are sensitive or not.

3.2 Data Collection

The data used will be gathered from up to date research papers, academic reports and books. The data will then be used for the parameters in the case study in which the theoretical models for the simulations in Matlab are created.

In order to get knowledge on how the wind varies during the year, data from SMHI was used and data in an hourly time frame for the average speed velocity (meters per second) during the period 2019 was chosen. The specifications on how the assumptions for the technical parameters were chosen are presented in chapter four.

For the solar PV, data for year 2019 for the Göteborg area from SMHI was used for the total number of solar hours per month. For further information, the technical assumptions for the different parameters will be presented in chapter four.

The litterature study was conducted by reading scientific papers. Three of them were chosen as the most relevant to this thesis and therefore they were presented in the previous chapter.

3.3 Program structure

For the simulations, Matlab was used. Three different scripts was constructed in Matlab where the first script contains the input parameters for the simulation, the second script is the simulation file based on the input parameters and the third script contains the graphical representations of the results from the second script. The scripts contains information about assumptions being made for the technical specifications, production and the environmental impact. This information is presented under the chapter case set up. The program was constructed in a way to enable ease of changing input parameters to fit the desired case set up. The first step was to get a fully functional program. This was done using a monthly basis time frame with average wind speed (m/s) and an average solar irradiation (W/m^2) for the simulation. The data set for this was taken from SMHI and Svenska Kraftnät for the year 2019. When this was done and the simulation worked, the time series was set to a more detailed level based on an hourly basis, which is the data set that is being used in order to generate the simulations and results presented in this thesis. The year used for the data set was 1 of January to 31 of December 2019. The sources of the information used is the same as when the program was created, i.e., SMHI and Svenska Kraftnät. The results are presented in both graphs and by numerical values.

3.4 Research Quality

The scientific papers that were read in order to perform this thesis are to a large extent taken via the Chalmers online resources library. They were written and published by well known institutions in Sweden such as consultancy firm Sweco and academia. The scientific papers have been made using a quantitative research method with assumptions being made for the different parameters used in those studies. When using assumptions and doing simulations for a long time frame, there is a possibility for source errors. The papers are well explained step by step so it is possible to replicate the studies.

4

Case set-up

This chapter presents the different cases that will be analysed and the corresponding input parameters that will be used in the calculations. The data for the current state is collected from various scientific reports and reports from institutions, whereas the data for the future scenario cases are based on approximations and predictive calculations.

4.1 Current state

The current state is based on Sweden's energy mix and will be used as underlying parameters for approximating the characteristics of a future energy mix with weather conditions from three different regions in Sweden. This section will present data in the areas of grid composition, cost of system and the environmental impact of the system.

4.1.1 Grid composition

Sweden's energy mix is largely comprised of nuclear and hydro in terms of generated electricity and an increasing share of renewables is being implemented in the system. Additionally, as seen from figures 4.3 and 4.4 the electricity demand is lower during the summer months and increases during the winter months.

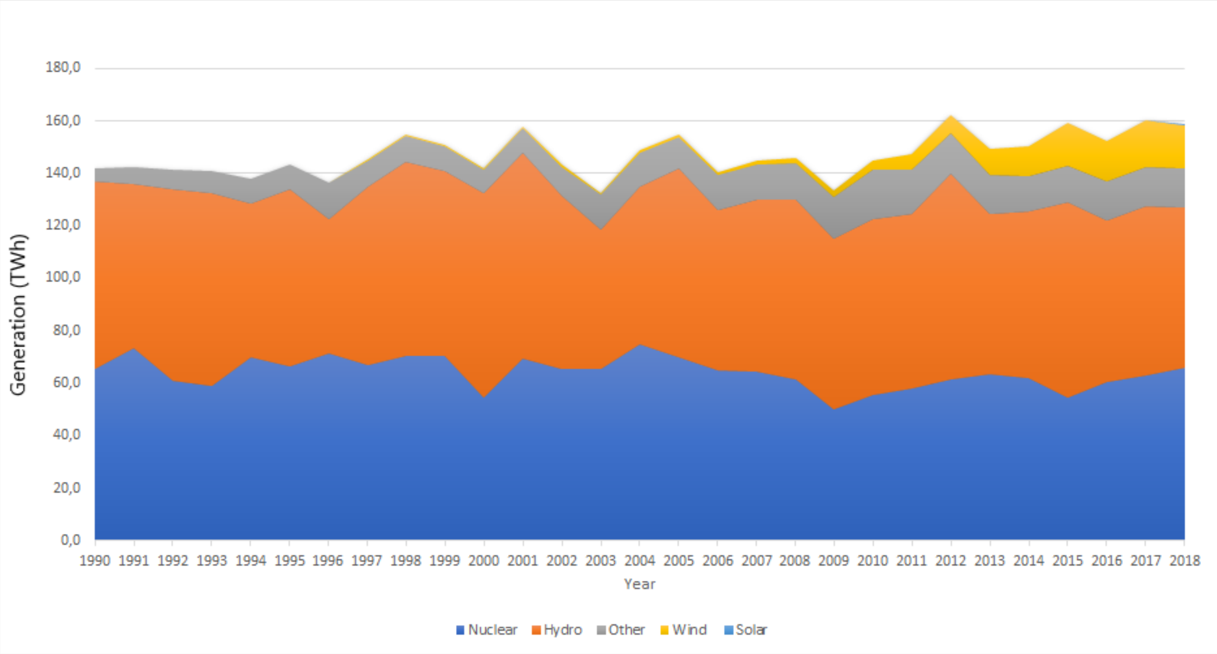

Figure 4.1: Electricity generation in Sweden from various technologies between 1990-2018

The figure 4.1 illustrates the energy mix and corresponding generation of electricity from each source in Sweden between the years 1990 to 2018. The figure reveals that the combination of nuclear and other (which incorporates thermal power stations and pumped-storage hydroelectricity) constitutes around 80.8 TWh of generated electricity.

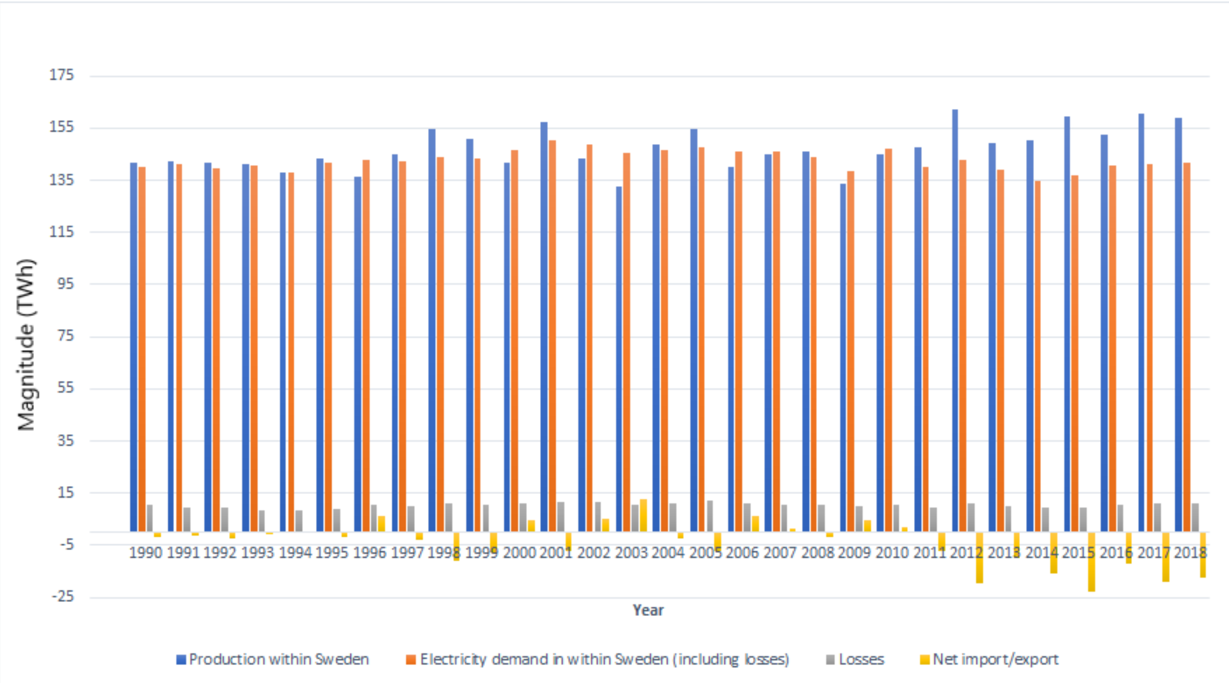

Figure 4.2: Overview of the energy system balance in Sweden between 1990-2018

Figure 4.2 depicts the total electricity generation within Sweden with the demand, losses and net import/export. Since 1990 the demand has been relatively stable and Sweden has been a net exporter between 2011 and 2018.

The data portrayed in figures 4.1 and 4.2 will act as a baseline for the approximations of the required electricity generation that needs to be substituted by wind and solar.

Currently, the Swedish national grid for electricity consists of 15,000 km of power lines, about 160 substations and switching stations and 16 overseas connections[30][31]. As of 2018, Sweden has 3569 wind turbines with an installed effect of 7300 MW. During year 2018, they produced 16.6 TWh. Grid connected solar cell panels accumulated to an installed effect of 411 MW in 2018[32]. Total production from solar PV:s during 2018 was 404 GWh[33].

Figure 4.3: Electricity Usage per Week

Figure 4.3 shows the electricity consumption per week in Sweden over the course of a year. The diagram depicts a decrease in electricity consumption during the summer months and an increase during the winter months [34].

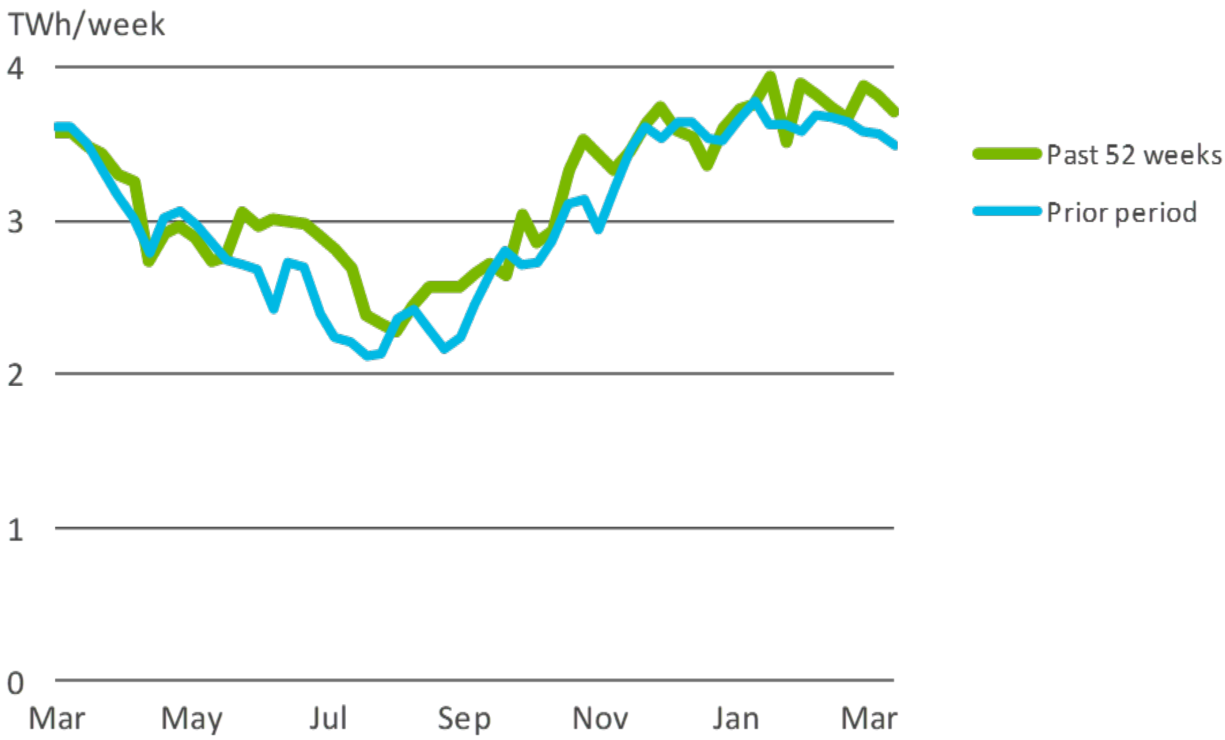

Figure 4.4: Power production per week

Figure 4.4 illustrates the data from Energiföretagen regarding the total electricity generation per week during the course of a year. The diagram shows the winter months have higher generation than during the summer months, in order to match the shifting demand [34].

4.1.2 Environmental impact of system

The data for the environmental impact from the hydrogen storage and the hydrogen electrolyser was performed using data from the National Renewable Energy Laboratory. Data from this report shows a value of 0.043 kg CO_2 per kg H2 generated by the electrolysis. This was then converted to the emissions in kg CO_2 eq per MWh generated electricity. For the storage capacity, the initial value from the same report shows 0.170 kg CO_2 per kg H2 for compression and storage. This value was then converted into CO_2 emissions per MWh stored electricity[35].

The environmental impact from lithium-ion batteries was found in a study made by IVL Swedish Environmental Research Institute. This data shows an emission level of 59-119 kg CO_2 eq per kWh capacity. From this it was decided to use a value of 100 kg CO_2 eq per kWh as a value for the parameter in this report[36].

In a report by the Swedish Energy Agency, the CO_2eq life cycle emission per kWh generated electricity from onshore wind turbines is estimated to be in the range from 20-38g CO_2 eq. From this, a value in the higher interval was chosen (35 kg CO_2 eq/MWh generated electricity). In the same report, an estimation for the emissions from solar PVs gives a CO_2 eq footprint of 88g per generated kWh electricity[14]. For the hydropower, the emission level is estimated to be around 12 kg for every MWh generated electricity[24]. The data used for determining the environmental impact of the different technologies is presented in table 4.1.

Table 4.1: Assumptions for the environmental impact.

Parameter	**Emissions [kg CO_2eq/MWh]**
Solar PV	88
Wind energy	35
Hydrogen electrolyser	0.86
Hydrogen storage	4.25
Lithium-ion battery	100 000
Hydropower	12

4.2 Description of formulation for case study

In order to get initial values on the parameters to start with, data from Energimyndigheten was used. The data for hydropower production is based on the hourly production during the year 2019 with the currently installed capacity of 16.3 GW. Additionally, the data for the load was based on the hourly consumption during the year 2019.

4.2.1 Description of parameters for ingoing components

For the parameters used for the lithium-ion battery, the assumption is that the energy storage is on a large scale with battery installations in or around the cities and villages. A comparison on what technology that can be found on the market today and in the near future was made. From this, the Tesla Megapack was chosen as a reference for the battery. Each of the battery packages has a maximum energy capacity of 2 MWh and at the initial state the CAPEX per kWh is assumed to be 2000 SEK[18]. Therefore the total CAPEX per battery is assumed to be 4 000 000 SEK. These batteries can be paired together to form a battery storage power station with an assumed maximum capacity of 1 GWh. The life expectancy is assumed to be 20 years.

Table 4.2: Assumptions for the different parameters of the battery.

Parameter	Value
Lithium-ion battery, CAPEX	2000 SEK/kWh
Maximum energy capacity	2 MWh
Total CAPEX per battery	4 000 000 SEK
Life expectancy	20 years

For the PEMFC and hydrogen storage parameters, values are assumed to be similar as in the article Hydrogen as a Long-Term Large-Scale Energy Storage Solution to Support Renewables by Kharel & Shabani[19].

Table 4.3: Assumptions for different parameters of hydrogen storage (PEMFC)

Components	Capital cost (SEK/KW)	O&M Cost (SEK/kW)	Lifetime (Year)	Efficiency
Electrolyser	20000	200	15	80%
Hydrogen Tank	4380 SEK/Kg	0	25	-
Fuel Cell	6000	0.8 SEK/op.h	40 000 h	45%

For the wind turbines, a fictional wind turbine was constructed based on data from wind turbines gathered by reading Vindkraftshandboken and the report Produktionskostnader för vindkraft i Sverige[37] [38].

Table 4.4: Parameters used for wind turbine

Parameter	Value
CAPEX of a 3 MW wind turbine	12.8 SEK/W SEK
OPEX of a 3 MW wind turbine	0,148 SEK/kWh
Life expectancy	25 years

A fictional polycrystalline solar PV was constructed based on the data from the report Teknisk-ekonomisk kostnadsbedömning av solceller i Sverige[39]. The CAPEX was set to 11,28 SEK/W with a life expectancy of 25 years.

The parameters used for hydropower was taken from a report by Nohlgren et al. (2014) [40], which describes the various electricity generating technologies and the corresponding costs of generation.

Table 4.5: Parameters used for solar PV.

Parameter	**Value**
CAPEX of 0.4 kW solar PV	11.28 SEK/W
OPEX of 0.4 kW solar PV	0.141 SEK/kWh
Life expectancy	25 years

Table 4.6: Parameters used for hydropower.

Parameter	**Value**
CAPEX of 90 MW hydropower	22.50 SEK/W
OPEX of 90 MW hydropower	0.10 SEK/kWh
Life expectancy	50 years

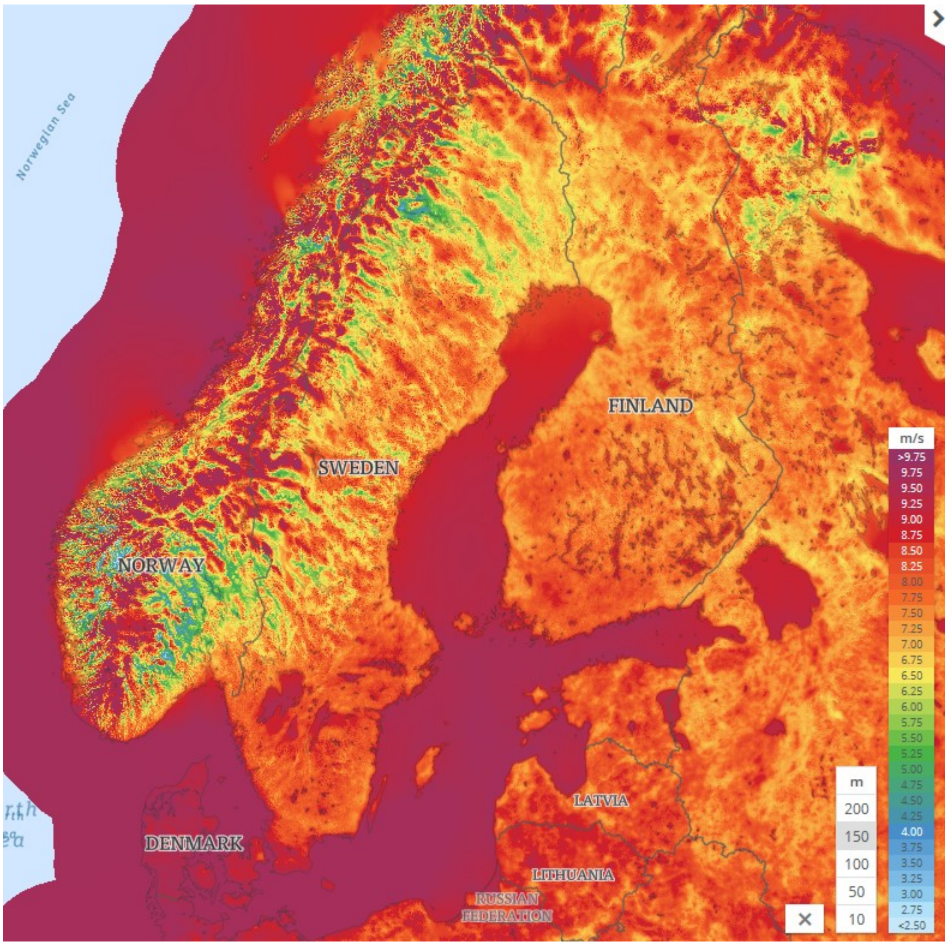

Figure 4.5: Wind conditions for Sweden at an altitude of 150 meters above sea level[41].

Figure 4.5 illustrates the wind conditions for Sweden at an altitude of 150 meters above sea level. In order to get time series with data that was realistic from a seasonal variation and diurnal variation perspective, the Swedish conditions were chosen. The fist step was to find areas suitable for wind turbines and solar PVs.

Here, the Global Wind Atlas was used to get a perception for the wind conditions. The altitude was set to 150 meters above sea level with mean wind speed conditions. When this was done, SMHI[42] was used and to find detailed data for the mean wind speed on a hourly basis measured over a 10 minutes period for the chosen area. The interval where the wind turbines generates electricity was set from 3 to 25 m/s, values less than 3 or above 25 were excluded and accounted for as 0 in the data series. For the global solar irradiance conditions, data from SMHI[43] was used with data series on a hourly basis using a mean value measured once per hour.

In the cases which includes hydropower, in order to get realistic conditions for what a hydro power system can look like, the data series used were the Swedish hydro power production for the year 2019 on a hourly basis from Svenska kraftnät[44].

4.3 Case 1

4.3.1 Case Composition

For case 1, the electricity demand (excluding exported electricity) will be maintained at around the same level as the year 2019 in Sweden, henceforth this parameter will be set to 132 TWh for this scenario. For this case, the generation will be composed of 52% from wind turbines, 10 % from solar PVs and 38% from hydro power. The hydro power will be kept at the same level as the electricity produced from hydropower for the year 2019 in Sweden. The excess generation of electricity based on wind profile and solar radiation will be stored in hydrogen and used with the PEMFC when the demand for electricity is higher than the production. In case 1, the production of solar PV's and wind turbines will come from an area with conditions similar to those on the Swedish west coast. The wind conditions for the island of Vinga outside Gothenburg were chosen with an hourly data series from SMHI for the year 2019. The measurements were made at a height of 10 meters above ground, corresponding to an altitude of 18 meters above sea level. For the solar PV, solar irradiation values were taken from SMHI for the city of Gothenburg for the year 2019. The simulation in Matlab was set to simulate every hour for the whole year. In order to speed up the simulation, the wind turbines was set to a 10 step simulation, meaning that Matlab will calculate with a solution of 10 wind turbines for each calculation. For the solar PV, the simulation was set to a 1000 step simulation.

4.4 Case 2, conditions similar to those in northern Sweden

4.4.1 Case composition

The second scenario is based on a grid composition with 54% coming from wind turbines, 36% coming from hydro power and 10% coming from solar PV. The production of electricity coming from hydro power will be kept at the same level as is case 1. The annual demand for electricity will be kept at 132 TWh. The storage capacity will consist of hydrogen tanks and then use PEMFC to generate electricity when the demand increases. The wind turbines and the solar PV panels will be located at the northern parts of Sweden. The data series for the wind conditions used in case 2 were taken from Frösön nearby the town of Östersund. The measurements were made at a height of 10 meters above ground, corresponding to an altitude of 376 meters above sea level. A problem occurred with this part of the work, out of the 8760 hours during 2019, wind speed measurements corresponding to 45 hours were missing for Frösön which meant that the data series was not complete. It was not possible to find the exact hours that were missing so in order to solve this problem, the last 45 hours of the year 2019 were duplicated and inserted again at the end of the time series in order to get 8760 hours. This was made in order to make the results from each case comparable. For the solar irradiation, data series for the town of Kiruna was used. The simulation in Matlab was set to simulate every hour for the whole year. In order to speed up the simulation, the wind turbines was set to a 10 step simulation, meaning that Matlab will calculate with a solution of 10 wind turbines for each calculation. For the solar PV, the simulation was set to a 1000 step simulation.

4.5 Case 3, no hydropower

4.5.1 Case composition

The third case is based on a grid composition with 90% of the electricity coming from wind turbines and 10% being generated by solar PV. As in the previous cases, the electricity demand will be kept at an annual demand of 132 TWh but no hydro power will be used. The storage will consist of tanks filled with hydrogen that will be used in the PEMFC.

The geographical location is the southern part of Sweden. The values for the wind conditions were taken from Sturup. The measurements were made at an height of 10 meters above ground level, corresponding to an altitude of 72 meters above sea level. The data series was not complete, 8752 values were accounted for, meaning that values for 8 hours were missing. It was not possible to find the exact days and hours for the values that were missing so in order to solve the problem, the last 8 values in the data series were duplicated and inserted again at the end of the time series. The values for solar irradiation were taken from the town of Lund. The simulation in Matlab was set to simulate every hour for the whole year. In order to speed up the simulation, the wind turbines was set to a 10 step simulation, meaning that Matlab will calculate with a solution of 10 wind turbines for each calculation. For the solar PV, the simulation was set to a 1000 step simulation.

4.6 Case 4, use of batteries

4.6.1 Case composition

The fourth case consists of the same system and input parameters for production and consumption as in case case one. The difference is that in this case, lithium ion batteries was added as storage capacity for the generated excess electricity. The data for the input parameters on the lithium ion batteries are presented in table 4.3. No PEMFC will be used in case 4. The simulation in Matlab was set to simulate every hour for the whole year. In order to speed up the simulation, the wind turbines was set to a 10 step simulation, meaning that Matlab will calculate with a solution of 10 wind turbines for each calculation. For the solar PV, the simulation was set to a 1000 step simulation.

5
Results

5.1 Case 1

5.1.1 Cost of system

The results obtained from the composition of case 1 is presented in table 5.1, where the hydrogen storage is also presented in its major components. According to the results, the primary operating cost post resides with the wind at 13.07 billion SEK annually. For the total fixed cost, the hydrogen storage system has the lowest. The solar PV system has the highest LCOE at 0.71 SEK/kWh, whereas hydropower and wind turbines are similar with 0.34 SEK/kWh and 0.32 SEK/kWh respectively. For the system, the total cost sum up to 2396 billion SEK. The highest cost is the total fixed cost, due to the investments in new renewable technology that needs to be built. Additionally, the LCoCE (levelized cost of consumed electricity) for the system shows the cost per consumed kWh based on the total system cost and total consumed electricity during the year.

Table 5.1: Shows the cost of the system for case 1

Technology	**AFC (BSEK/yr)**	**Total Fixed Cost (BSEK)**	**LCOE (SEK/kWh)**	**AOC(BSEK/yr)**	**Total OPEX (BSEK)**	**Total Cost (BSEK)**
Hydropower	20.09	1 005	0.34	6.51	326	1 330
Wind	15.29	382	0.32	13.07	327	709
Solar PV	9.62	241	0.71	2.40	60	301
Electrolyser	1.43	21	-	2.27	34	56
Storage Tank	0.02	0.57	-	0	0	0.57
Fuel Cell	0.003	0.026	-	3 082 SEK	32 000 SEK	0.026
Hydrogen Storage	1.46	22	-	2.27	34	56
	AFC (BSEK/yr)	**Total Fixed Cost (BSEK)**	**LCoCE (SEK/kWh)**	**AOC(BSEK/yr)**	**Total OPEX (BSEK)**	**Total Cost (BSEK)**
System	46	1 649	18	24	746	2 396

5.1.2 Grid balance

The table below shows the generation and consumption of electricity in case 1. The total production in the system is 170.42 TWh. The overgeneration will be used as storage capacity to convert the electricity into hydrogen and use in the fuel cell when there is a demand for electricity. The excess electricity is the remaining stored generation at the end of the year. Of the intermittent sources, wind is the most contributing with an annual generation of 88.28 TWh.

Table 5.2: Grid balance case 1

	Generation/Consumption (TWh)
Hydropower	65.10
Wind	88.28
Solar PV	17.04
Production from Hydrogen	20.09
Total Consumption	132.15
Total Generation	170.42
Overgeneration	55.79
Demand Remaining	17.52
Excess electricity	2.57

The table below shows the grid balance for case 1. The capacity from the installed base of wind turbines is the largest with 16833 MW. The capacity from the hydropower will work as a battery to even out the differences in production and consumption during peak loads. Solar as the lowest CF capacity, mainly because of the chosen location for the data is located in the northern region of the northern hemisphere.

Table 5.3: Capacity for case 1

Capacity Hydropower	16 300 MW
Capacity Wind	16 833 MW
Capacity Solar PV	12 021 MW
CF Hydropower	0.46
CF Wind	0.60
CF Solar PV	0.16

The figure below shows the annual production of energy coming from wind. As can be seen, there are variations between the hours and seasons for this intermittent energy source. The maximum generation from the wind turbines are reached continuously with exceptions for parts of the spring and the summer.

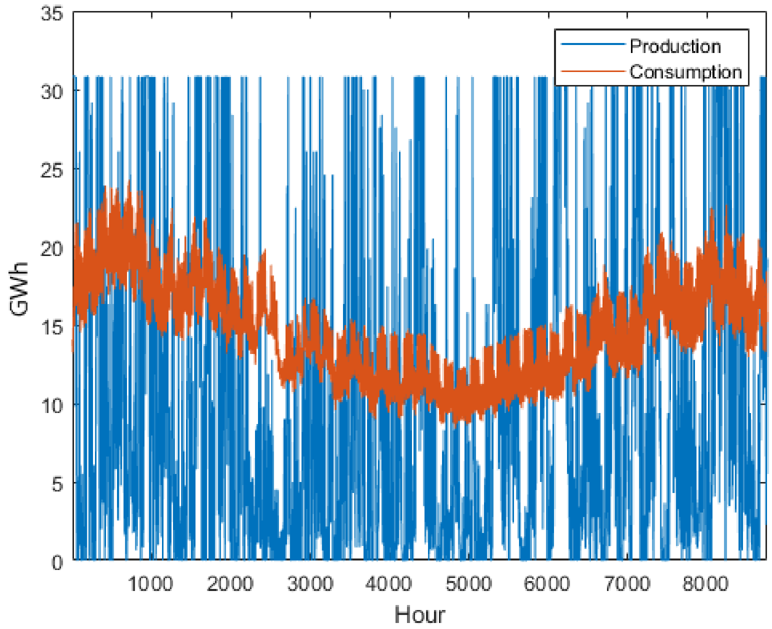

Figure 5.1: Wind power generation in relation to total consumption in case 1

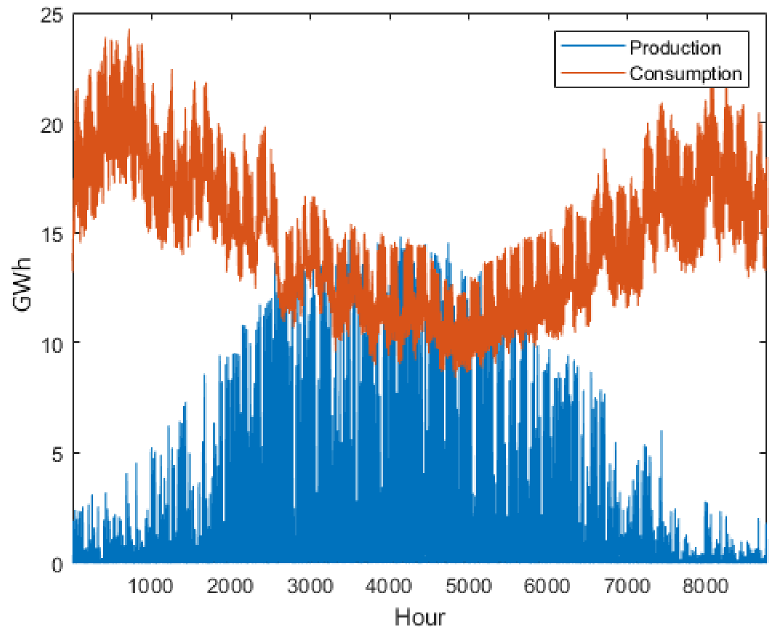

Figure 5.2: Solar PV generation in relation to total consumption in case 1

The city of Gothenburg was the location for the solar PV in case 1. As can be seen, up in the Nordic region of the northern hemisphere, it is possible to see a clear variation between the seasons. This makes it necessarily to combine the solar PV with other sources of renewables. Figure 5.1 and 5.2 will be combined together with the hydropower to form the total annual production which will be presented in figure 5.3.

The figure below shows the total annual production of electricity in blue and the total consumption in orange. As can be seen, the consumption varies between the seasons. The variation in the production of electricity is due to the intermittent energy sources in case 1. During overproduction, electricity will be converted to hydrogen and then used in the PEMFC when the demand for electricity is higher than the supply.

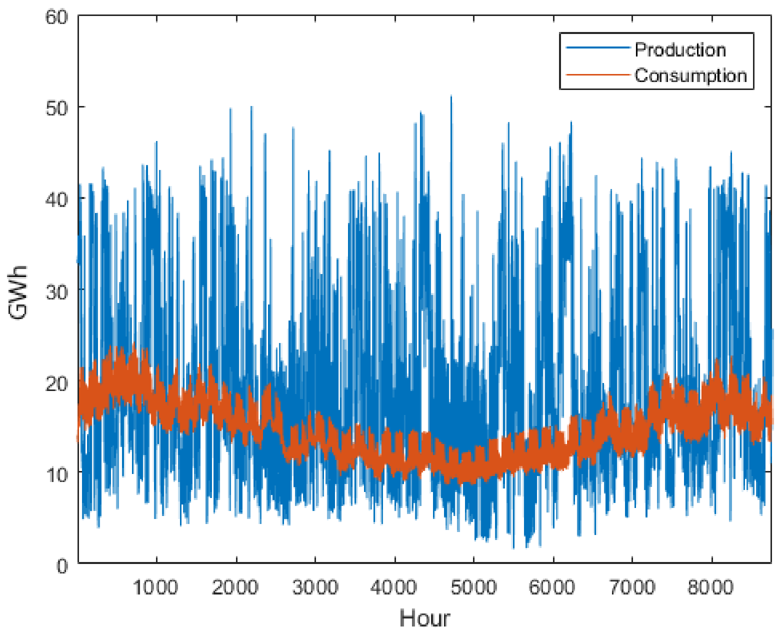

Figure 5.3: Total electricity generation in relation to total consumption in case 1

The generation curve below shows that the production has its maximum production between 40 and 50 MWh. For most of the time, the production keeps above 10 MWh. It is due to the intermittent energy sources solar PV and wind energy that the curve looks like it does. It has a fairly linear curve as a result of the stability provided by hydropower.

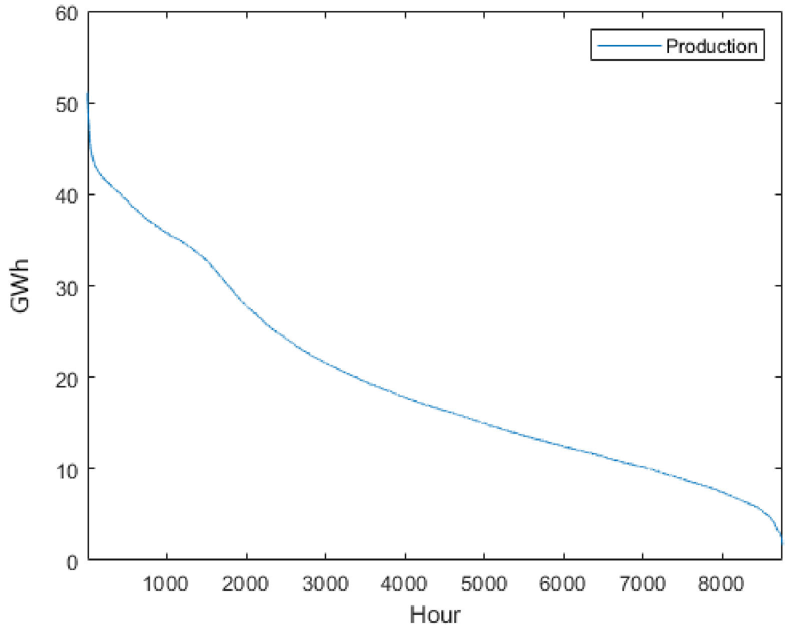

Figure 5.4: Generation curve for case 1

5.1.3 Environmental impact of system

The environmental impact of case 1 is presented below. Hydrogen storage with 0.24 Mtonnes CO_2 gives the lowest contribution to the emissions. The wind turbines have the highest CO_2 impact with 3.09 Mtonnes annually. Figure 5.5 gives a graphical presentation with an logarithmic scale on the y-axis.

Table 5.4: CO_2 emissions from each technology in case 1

Technology	**CO_2 emissions (Mtonne CO_2)**
Hydropower	0.78
Wind	3.09
Solar PV	1.50
Electrolyser	0.05
Storage Tank	0.19
Fuel Cell	0
Hydrogen Storage	0.24

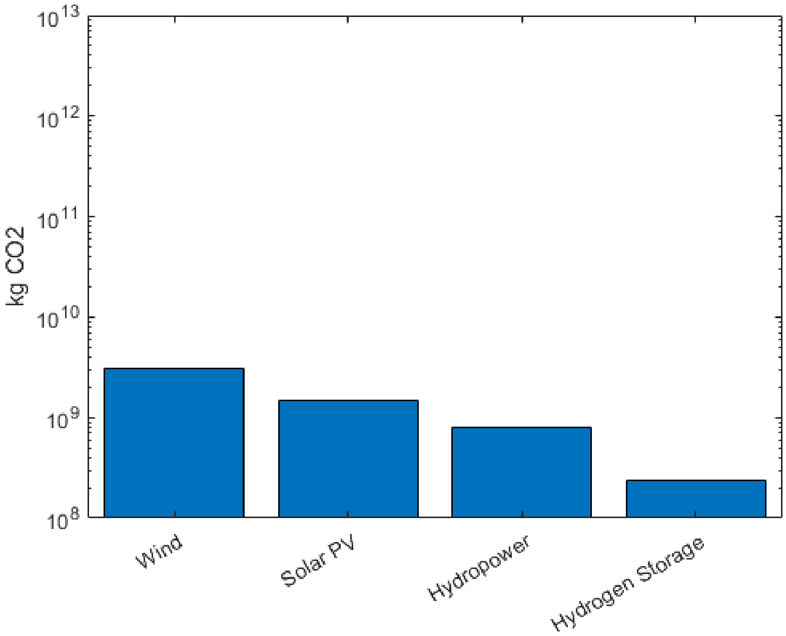

Figure 5.5: CO_2 emissions from each technology in case 1

5.2 Case 2

5.2.1 Cost of system

The results for the second case composition, presented in table 5.5, shows a total cost of 3679 BSEK, where the largest cost is associated with the wind turbines followed by hydropower, solar PVs and hydrogen storage. The solar PVs have the lowest running cost in comparison to the other technologies, followed by the hydrogen system, in which the largest cost within the hydrogen system resides with the electrolyser.

Table 5.5: Cost case 2

Technology	AFC (BSEK/yr)	Total Fixed Cost (BSEK)	LCOE (SEK/kWh)	AOC(BSEK/yr)	Total OPEX (BSEK)	Total Cost (BSEK)
Hydropower	20.08	1 005	0.34	6.51	326	1 330
Wind	60.52	1 513	0.76	14.67	367	1 880
Solar PV	12.66	316	0.83	2.57	64	381
Electrolyser	2.49	37	-	3.33	50	87
Storage Tank	0.04	0.89	-	0	0	0.89
Fuel Cell	0.002	0.02	-	3 442 SEK	32 000 SEK	0.02
Hydrogen Storage	2.53	38	-	3.33	50	88
	AFC (BSEK/yr)	**Total Fixed Cost (BSEK)**	**LCoCE (SEK/kWh)**	**AOC(BSEK/yr)**	**Total OPEX (BSEK)**	**Total Cost (BSEK)**
System	96	2 872	28	27	807	3 679

5.2.2 Grid balance

According to the electricity generation results of the simulation of case 2, shown in table 5.6, the total electricity generation was 182.45 TWh, which is substantially higher than the total consumption of 132.15 TWh. The reason behind this is that there are some losses in the storage system due to the efficiency of the electrolyser and the fuel cell, resulting in the need for an overgeneration of electricity in order to ensure the demand can be met during hours of underproduction. The hydrogen storage system stores correspondingly around 74.27 TWh, which is relatively large for the system albeit necessary due to the nature of intermittency and the effect it has when incorporating a larger share of renewables in the system composition. With an increased efficiency of the hydrogen storage system, the need for this magnitude of overgeneration will be reduced, therefore enabling a reduction of storage capacity and in extension the cost of the system. Additionally, with a reduced level of overgeneration, the stability of the system frequency will increase, thus reducing the need for system stabilizing ancillary services.

Table 5.6: Grid balance case 2

	Generation/Consumption (TWh)
Hydropower	65.10
Wind	99.11
Solar PV	18.24
Production from Hydrogen	26.74
Total Consumption	132.15
Total Generation	182.45
Overgeneration	74.27
Demand Remaining	23.97
Excess electricity	2.77

Table 5.7 shows the total installed capacity of each technology and the corresponding capacity factors in case 2. With the 3 MW wind turbines used in this case composition, the capacity factor of 17 % is quite low if compared with for instance the Danish off-shore wind turbines (around 2.3 MW peak power) that reach capacity factors of around 40 % [45]. There are numerous reasons to this such as the wind profile in Frösön and the design of the wind turbines. Having a low capacity factor is also an indication that the potential electricity generation of the wind turbine could be increased, however, in this region it would be more financially viable to invest in wind turbines with a lower peak power rating since the capacity factor with a 3 MW wind turbine is relatively low. The capacity factor of the solar PVs are around what is expected in the northern region of Sweden as large parts of the year have low solar irradiance levels for the solar PVs to convert into electricity.

Table 5.7: Capacity case 2

Capacity Hydropower	16 300 MW
Capacity Wind	66 633 MW
Capacity Solar PV	15 817 MW
CF Hydropower	0.46
CF Wind	0.17
CF Solar PV	0.13

The following figures 5.6-5.9 are visualisations of the total hourly electricity generation in comparison to the total consumption over the course of a year. Figure 5.6 shows that hydropower has a stable electricity production over the year in comparison to wind and solar which have high variation in production due to the intermittent nature of the energy source. The hydropower in case 2 was kept at the same level as the production from Swedens hydropower during 2019, therefore it could likely have a slight larger variation in order to accommodate the intermittent nature of solar and wind technology.

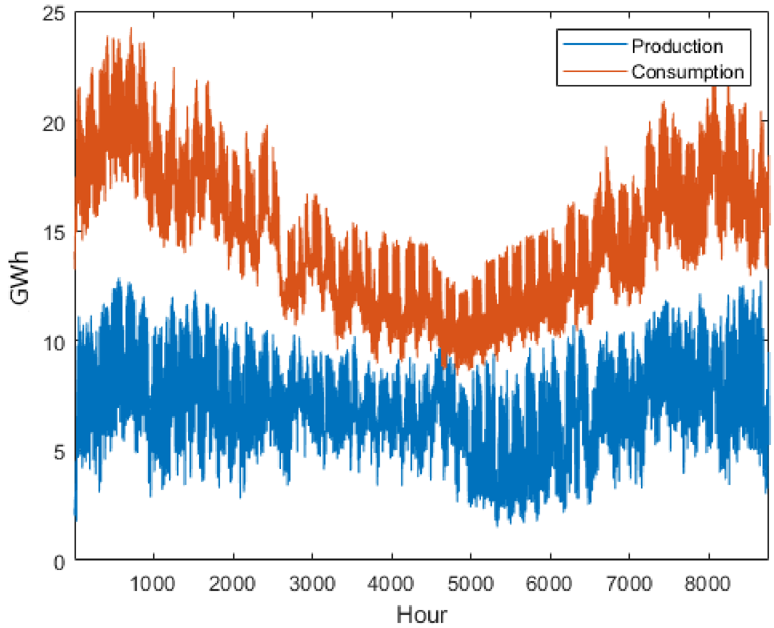

Figure 5.6: Hydropower generation in relation to total consumption in case 2

Figure 5.7 shows the intermittent nature of producing electricity from wind turbines. Due to the high levels of irregularity in production, it follows that a large storage system is required in order to ensure that the demand is met each hour. The electricity production is peaked when wind speeds range from 11 m/s to 25 m/s, however if the generator would be able to increase power output as the wind speed increases between 11 m/s to 25 m/s instead of stalling, there would require fewer wind turbines to meet the demand, albeit at a higher cost of generators. In this case, the total amount of wind turbines required to generate a corresponding 54.35 % of total production is 22211 which covers a total area of around 7403 km^2. Similar to wind but with a different profile, figure 5.8 shows the intermittent nature of solar irradiance in the area. In order to produce 10 % of the required electricity production, it would require almost 40 million solar panels in this case covering a total area of around 211 km^2.

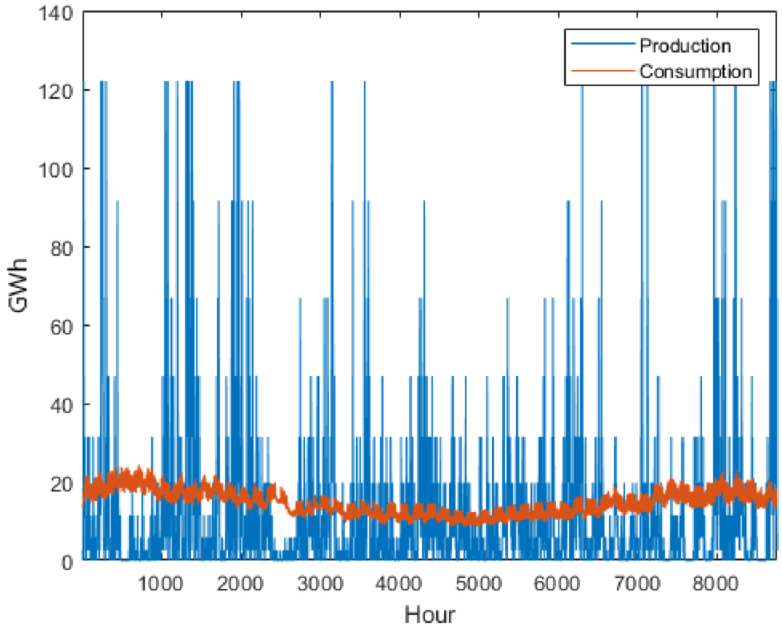

Figure 5.7: Wind power generation in relation to total consumption in case 2

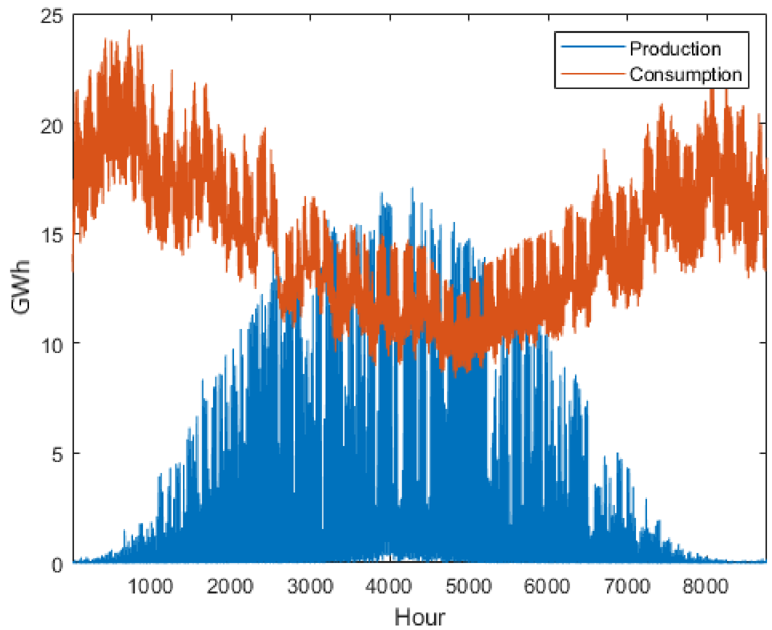

Figure 5.8: Solar PV generation in relation to total consumption in case 2

Figure 5.9 shows the aggregated production from hydro, wind and solar in relation to the total consumption. Figure 5.10 shows the generation curve for case 2. The steep slope in the beginning of the generation curve is a result of the high production output from the wind turbines and as the slope levels off it reaches a more even production level, primarily due to the stable production from hydropower.

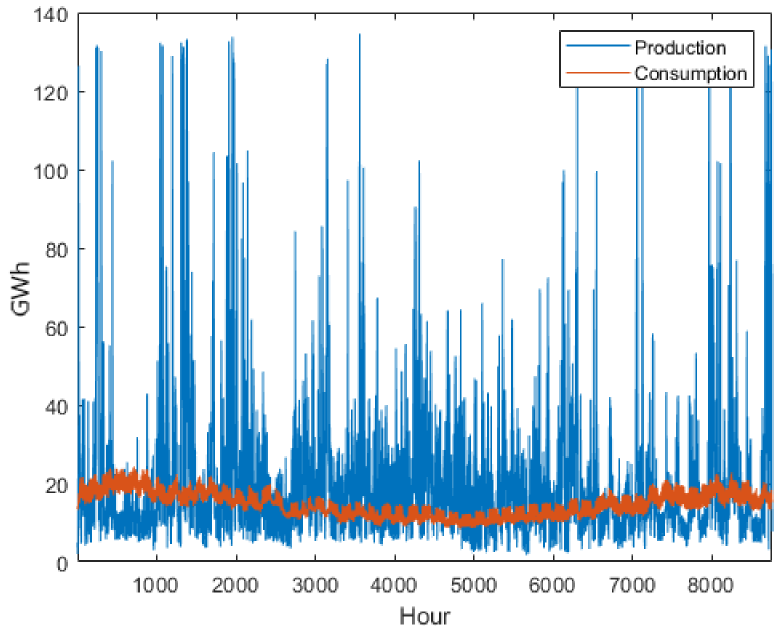

Figure 5.9: Total electricity generation in relation to total consumption in case 2

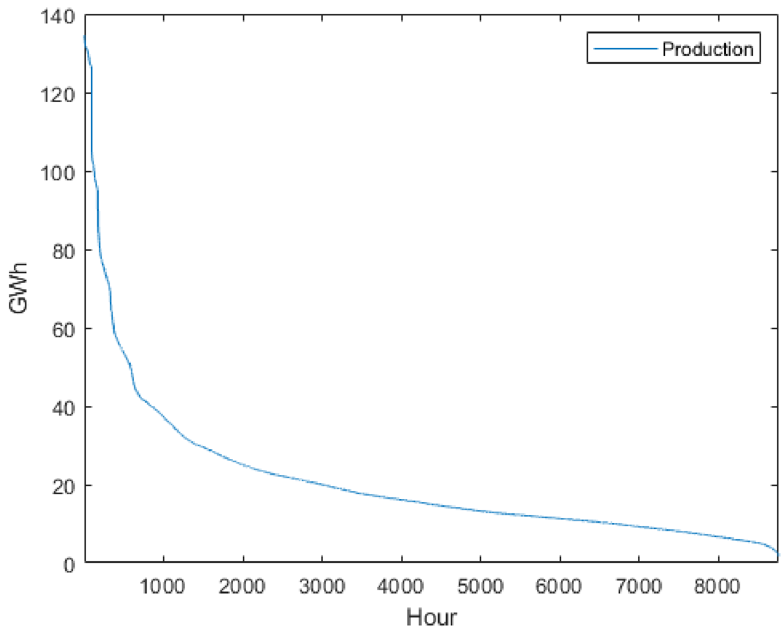

Figure 5.10: Generation curve for case 2

5.2.3 Environmental impact of system

Table 5.8 shows that the major environmental impact from case 2 comes from the wind turbines as it did in case 1. For the hydrogen system, in addition to the required components, the environmental impact depends largely on what electricity source is used for the electrolyser. In this case, the source is from either wind or solar power depending on the time of utilisation, which significantly lowers the emission impact of the electrolyser and consequently the hydrogen storage system as a whole. Additionally, the environmental impact from the storage tank is primarily from the material required to store the hydrogen in a pressurised environment of around 200 bar.

Table 5.8: Environmental impact from case 2

Technology	**CO_2 emissions (Mtonne CO_2)**
Hydropower	0.78
Wind	3.47
Solar PV	1.61
Electrolyser	0.06
Storage Tank	0.25
Fuel Cell	0
Hydrogen Storage	0.32

The data from table 5.8 is represented graphically in figure 5.11 in a logarithmic scale, which shows the disparity between the storage system and the technologies for electricity production.

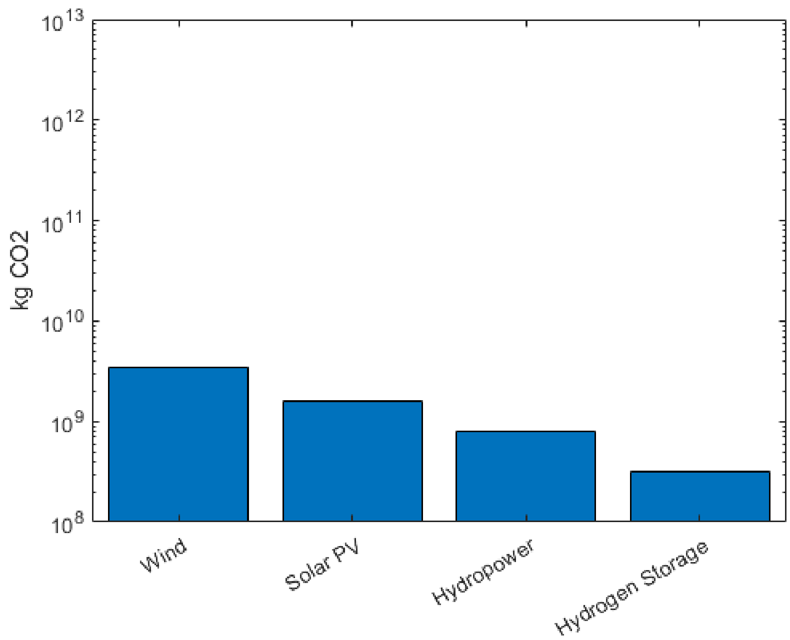

Figure 5.11: CO_2 emissions from each technology in case 2

5.3 Case 3

5.3.1 Cost of system

In case 3, the total cost of the system amount to around 4699 BSEK, which is shown in table 5.9. In this case, due to the absence of hydropower, the amount of wind turbines and solar panels have increased, however the cost change in wind turbines is much larger than the change in solar panels in relation to cases 1 and 2. The cost of wind turbines is substantially larger in this case, as well as the hydrogen storage. The increase in cost for wind turbines is naturally a result of having to produce 90 % of the total electricity generation, consequently increasing the investment costs. The increase in hydrogen storage is a result of removing a baseload power plant in hydropower, thus increasing the variation in production and henceforth requiring larger capacity for the storage system.

Table 5.9: Cost of system components in case 3

Technology	AFC (BSEK/yr)	Total Fixed Cost (BSEK)	LCOE (SEK/kWh)	AOC(BSEK/yr)	Total OPEX (BSEK)	Total Cost (BSEK)
Wind	95.50	2388	0.62	30.08	752	3 139
Solar PV	12.24	306	0.68	3.18	80	385
Electrolyser	4.34	65	-	6.86	103	168
Storage Tank	0.06	1.43	-	0	0	1.43
Fuel Cell	0.005	0.04	-	3 731 SEK	32 000 SEK	0.04
Hydrogen Storage	4.40	67	-	6.86	103	169
	AFC (BSEK/yr)	**Total Fixed Cost (BSEK)**	**LCoCE (SEK/kWh)**	**AOC(BSEK/yr)**	**Total OPEX (BSEK)**	**Total Cost (BSEK)**
System	132	3 765	36	40	934	4 699

5.3.2 Grid balance

Table 5.10 shows the total generation from each technology and the total consumption. In case 3 the total generation is much higher than in the previous cases, primarily due to the omition of hydropower which leads to the requirement of a larger storage system in order to accomodate the intermittency of wind and solar. The remaining excess electricity from the system resulted in 3.76 TWh, which is the remaining stored electricity within the hydrogen storage system.

Table 5.10: Grid balance case 3

	Generation/Consumption (TWh)
Wind	203.21
Solar PV	22.57
Production from Hydrogen	50.55
Total Consumption	132.15
Total Generation	225.78
Overgeneration	140.42
Demand Remaining	46.79
Excess electricity	3.76

With the absence of hydropower, the amount of installed capacity for wind turbines increases drastically in comparison to case 1 and 2, reaching a total of around 105 GW.

Table 5.11: Capacity case 3

Capacity Wind	105 153 MW
Capacity Solar PV	15 289 MW
CF Wind	0.22
CF Solar PV	0.17

Figure 5.12 shows that the wind profile leads to a generation that lies somewhere between case 1 and 2 in terms of the ideal level for wind turbines. The profile reveals that there are not many hours where the wind speeds reach the ranges of 11 m/s to 25 m/s, which is shown by the amount of peaks in the figure.

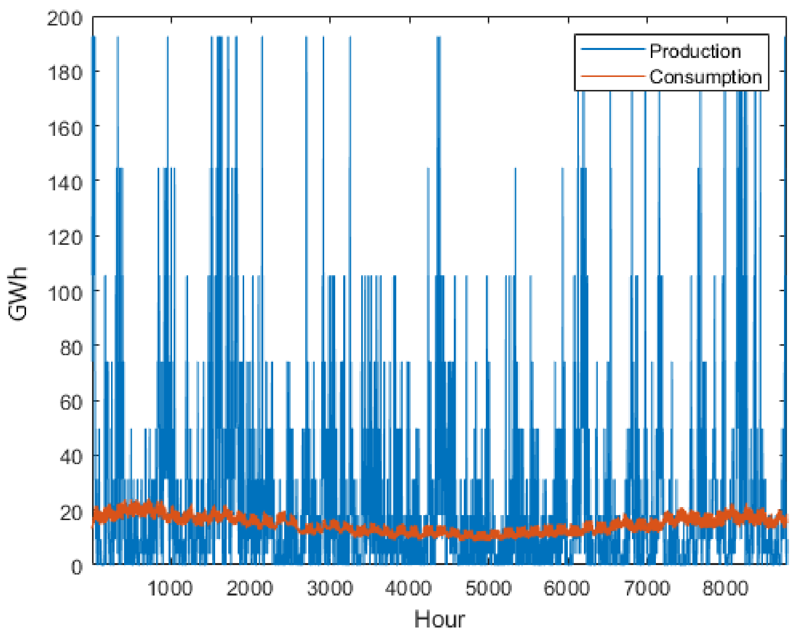

Figure 5.12: Wind power generation in relation to total consumption in case 3

The electricity generation from solar PVs in case 3, visualised in figure 5.13 is relatively similar to the corresponding profile in case 1.

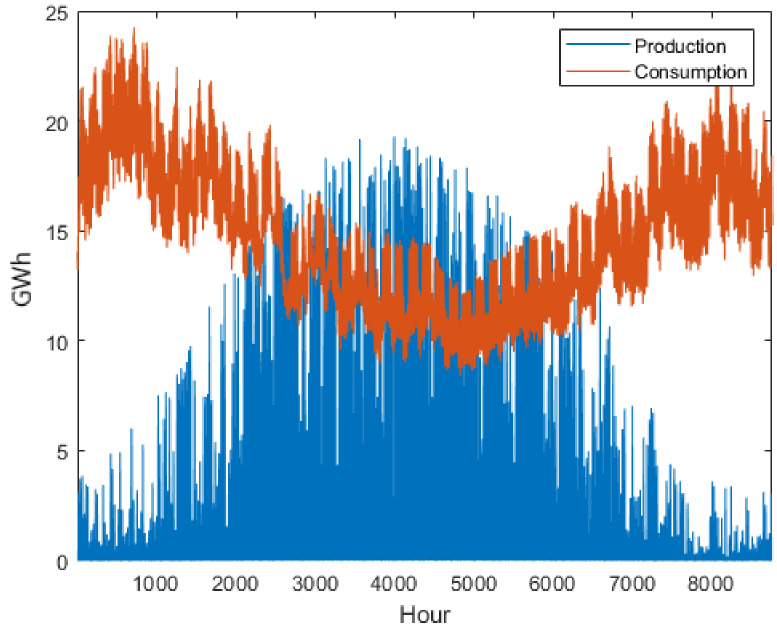

Figure 5.13: Solar PV generation in relation to total consumption in case 3

The electricity generation from the wind turbines in case 3 is almost identical to the total electricity generation profile shown in figure 5.14, which is expected as the production from wind corresponds to 90 % in this case. Just like cases 1 and 2, the composition of the system requires a large storage system due to the intermittent nature of the technologies.

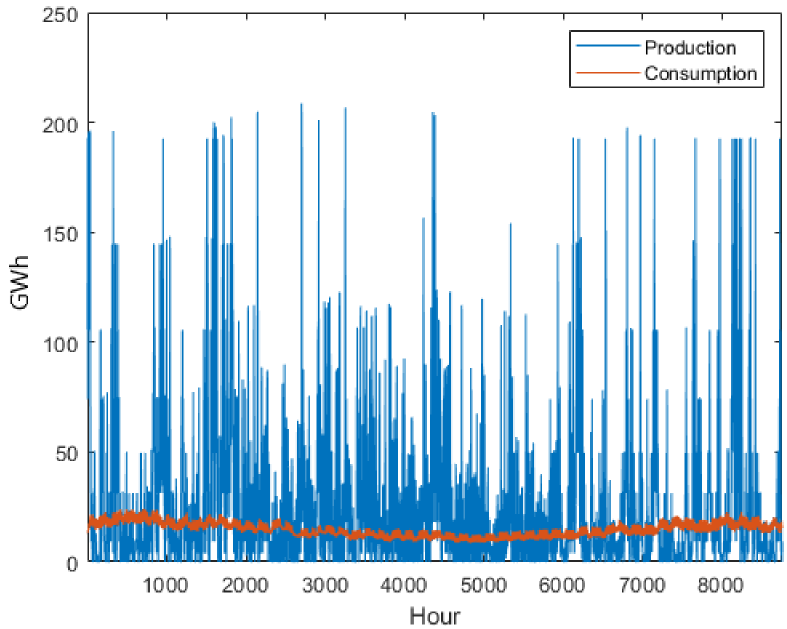

Figure 5.14: Total electricity generation in relation to total consumption in case 3

In comparison to the generation curve from case 1 and 2, the generation curve from case 3 is not as smooth and descends in an incremental nature, shown in figure 5.15. The reason to this result is due to removing the stable electricity production supplied by hydropower in the previous cases. An important distinction between the cases is also that the electricity production reaches 0 in case 3 during certain hours, whereas in the previous cases there is always production of electricity present. This shows that in the region of southern Sweden, there will be hours where there is no production from wind or solar, which will occur more frequently during the winter season than during the summer season.

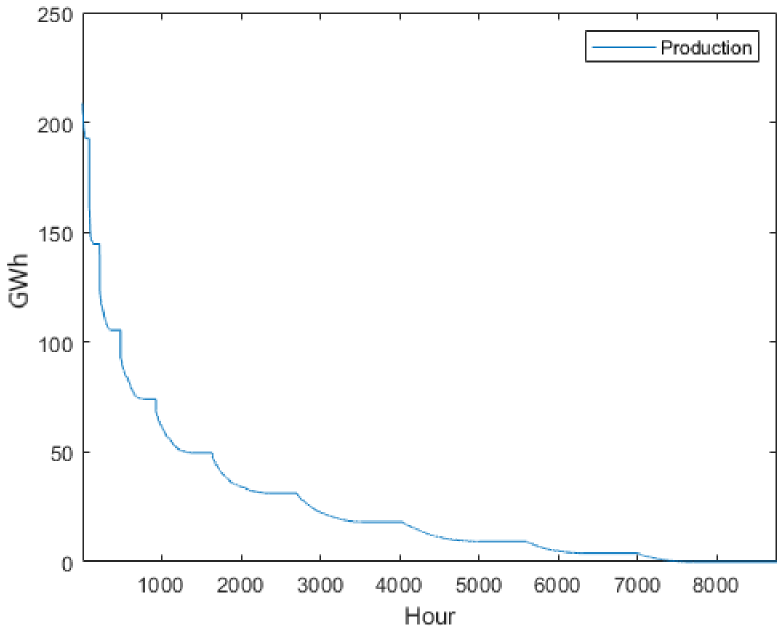

Figure 5.15: Generation curve for case 3

5.3.3 Environmental impact of system

The environmental impact from case 3 is presented in table 5.12, where the emissions from the wind turbines has the highest environmental impact and the hydrogen storage has the lowest. An important aspect to note is that these emissions are not compared on an equal electricity-production scale. The emissions from solar is a approximately a third of the emissions from wind, however, the wind turbines produce 90 % of the total generation in comparison to the 10% produced by solar PVs.

Table 5.12: CO_2 emissions from each technology in case 3

Technology	**CO_2 emissions (Mtonne CO_2)**
Wind	7.11
Solar PV	1.99
Electrolyser	0.12
Storage Tank	0.48
Fuel Cell	0
Hydrogen Storage	0.60

Figure 5.16 visualizes the results from table 5.12 in a logarithmic scale, showing the difference between the various technologies.

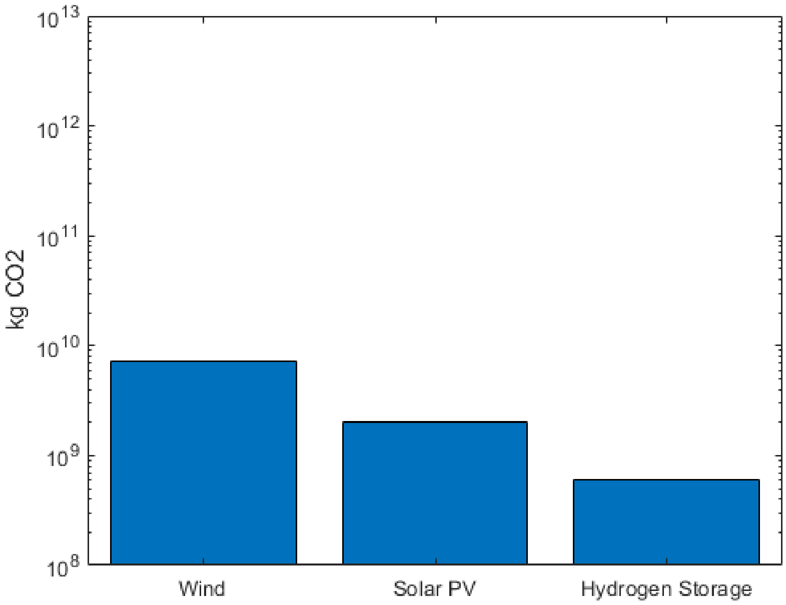

Figure 5.16: CO_2 emissions from each technology in case 3

5.4 Case 4

5.4.1 Cost of system

The results from case 4, as presented in table 5.13, shows that the cost of utilising a storage system based on lithium-ion batteries is extremely expensive in a utility-scale application. The costs far exceed that of the previous cases which has a hydrogen based storage system, up to a factor of around 18. However, the efficiency of a battery storage system is close to 100 % whereas there are greater losses to be accounted for in the hydrogen based storage system. Additionally, it is important to note that the input parameters for these cases are based on values of the market today and consideration has not been taken into account for the potential cost decrease of these systems. Battery storage can eventually be cost competitive but in accordance to the results from case 4 it is not financially viable to have a storage system at this scale based on lithium-ion batteries.

Table 5.13: Case 4, cost of system

Technology	**AFC (BSEK/yr)**	**Total Fixed Cost (BSEK)**	**LCOE (SEK/kWh)**	**AOC(BSEK/yr)**	**Total OPEX (BSEK)**	**Total Cost (BSEK)**
Hydropower	20.08	1 005	0.34	6.51	326	1 330
Wind	9.35	234	0.32	7.99	200	433
Solar PV	7.47	187	0.71	1.87	47	233
Battery Storage	1 398.10	27 961	-	-	-	27 961
	AFC (BSEK/yr)	**Total Fixed Cost (BSEK)**	**LCoCE (SEK/kWh)**	**AOC(BSEK/yr)**	**Total OPEX (BSEK)**	**Total Cost (BSEK)**
System	1 435	29 386	182	16	572	29 958

5.4.2 Grid balance

Table 5.14 reveals that case 4 has a total generation that is very close to the total consumption, which is largely due to the efficiency of batteries, which in this case was estimated to be at 100 % and thus requiring much less overgeneration in comparison to the other cases with a hydrogen storage system. By minimising the amount of wind and solar needed, in relation to cases 1 and 2, the disparity between the consumption and the generation is reduced. By reducing the disparity between load and production, the risk of deviation of the system frequency from the acceptable range is reduced.

Table 5.14: Grid balance case 4

	Generation/Consumption (TWh)
Hydropower	65.10
Wind	53.98
Solar PV	13.23
Battery Storage	23.78
Total Consumption	132.15
Total Generation	132.32
Overgeneration	23.78
Demand Remaining	23.62
Excess electricity	0.17

In correlation with the results presented in table 5.14, table 5.15 reveals that the amount of installed capacity from wind and solar can be reduced, thus reducing the cost of investment for wind turbines and solar PVs.

Table 5.15: Capacity case 4

Capacity Hydropower	16 300 MW
Capacity Wind	10 293 MW
Capacity Solar PV	9 335 MW
CF Hydropower	0.46
CF Wind	0.60
CF Solar PV	0.16

Figure 5.17 shows the hourly electricity production from hydropower and is kept at the same level of production as in cases 1 and 2.

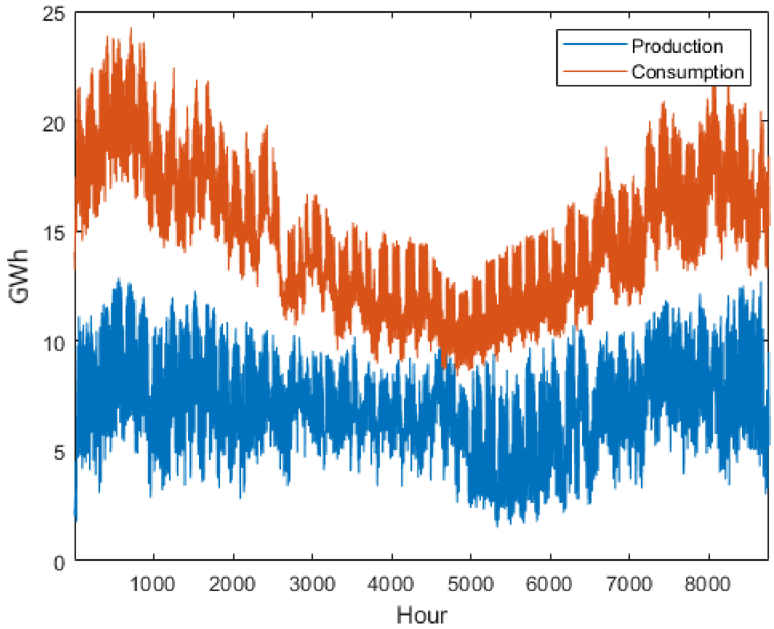

Figure 5.17: Hydropower generation in relation to total consumption in case 4

Due to the assumption of having an efficiency of 100 % for the battery storage system, the requirement of electricity production to far exceed the consumption level during certain hours is void and therefore the production from wind is much less than in case 1. Also, as mentioned in case 1, the wind profile outside the coast of Gothenburg is favourable for wind turbines, which is visualised in figure 5.18. The production is relatively stable in relation to the regions in case 2 and 3, which will be benefitial in terms of maintaining the system frequency.

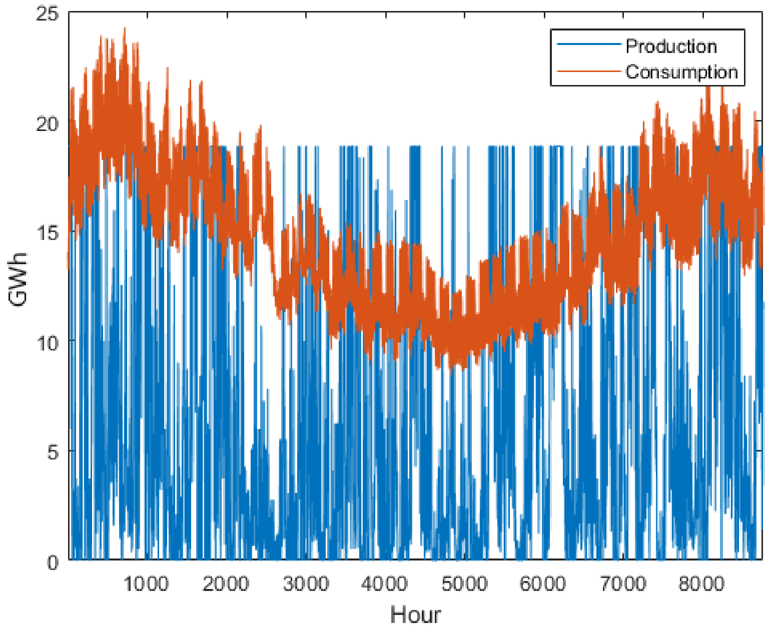

Figure 5.18: Wind power generation in relation to total consumption in case 4

The effects of a storage system with high efficiency is consequentially identical for the production from solar PVs as wind turbines, where figure 5.19 shows the reduced amount of production needed in comparison to case 1.

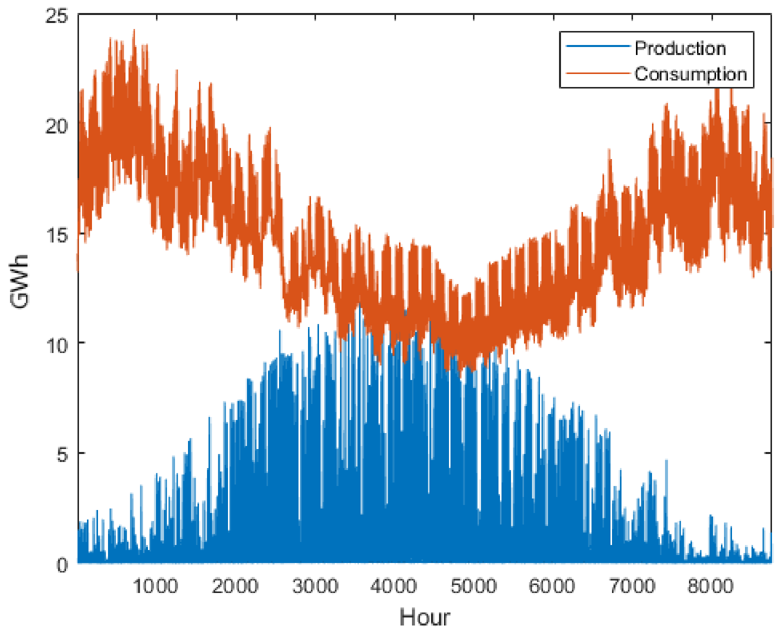

Figure 5.19: Solar PV generation in relation to total consumption in case 4

Figure 5.20 visualises how the aggregated production has a reduced deviation from the consumption curve in comparison to cases 1-3. Despite the reduced deviation, there is still a relatively high disparity between the consumption curve and production curve which increases the risk of frequency levels dropping to below the accepted range of deviation from the ideal frequency level. This issue is partly mitigated by the use of a battery storage system due to it's possibility of a short response time, which is a key element in maintaining quality electricity and functionality in the system.

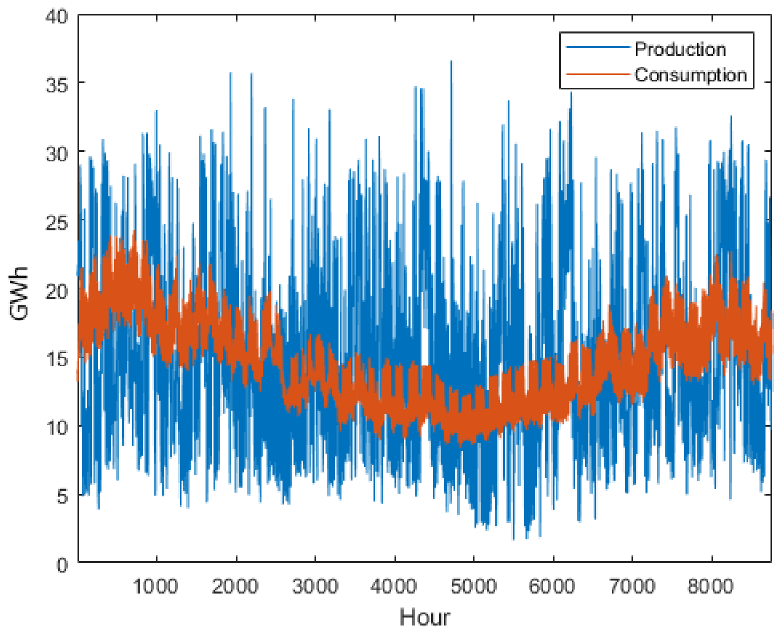

Figure 5.20: Total electricity generation in relation to total consumption in case 4

Due to the reduced amount of wind turbines and solar PVs required for case 4, the effect of the intermittent technologies are reduced which is illustrated in figure 5.21. The curve is much smoother and has a lower rate of descent as a result of the increased percentage of the system composition accounted for by the relatively stable production from hydropower.

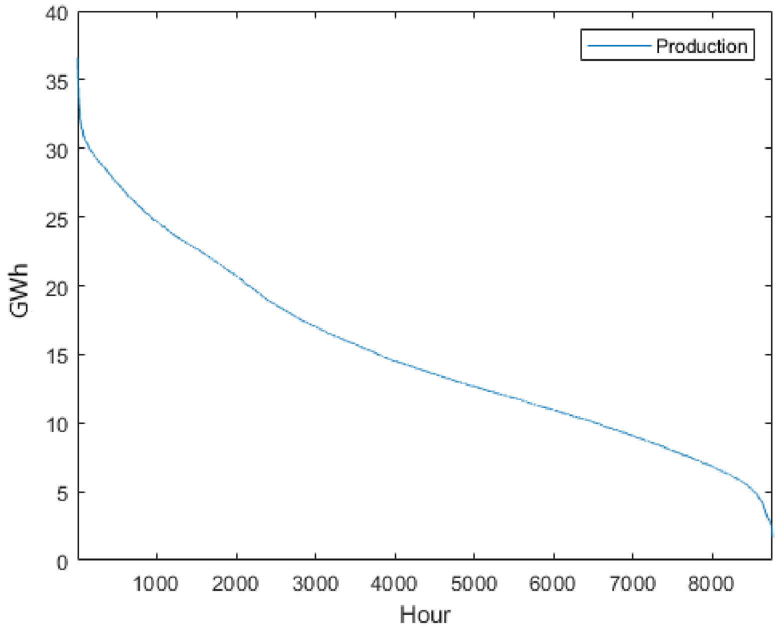

Figure 5.21: Generation curve for case 4

5.4.3 Environmental impact of system

Despite the benefits of the quick response time of a battery storage system and the reduced risk of frequency issues, the drawback of utility-scale battery storage is the consequential CO2 emissions, apart from the size of the cost associated with the storage system. Table 5.16 presents the impact a utility-scale storage system comprised of lithium-ion batteries in comparison to the generation technologies. However, as batteries have reduced in cost it may also subsequently reduce the corresponding emission levels from further research and development.

Table 5.16: Environmental impact from case 4

Technology	CO_2 emissions (Mtonne CO_2)
Hydropower	0.78
Wind	1.89
Solar PV	1.16
Battery Storage	871.14

Figure 5.22 shows the visualisation of table 5.16 in a logarithmic scale, highlighting the difference in emissions between the major system components. The battery storage system has by far the highest emission level in this case, which can be compared to the relatively low emission levels from the hydrogen storage system in the previous cases.

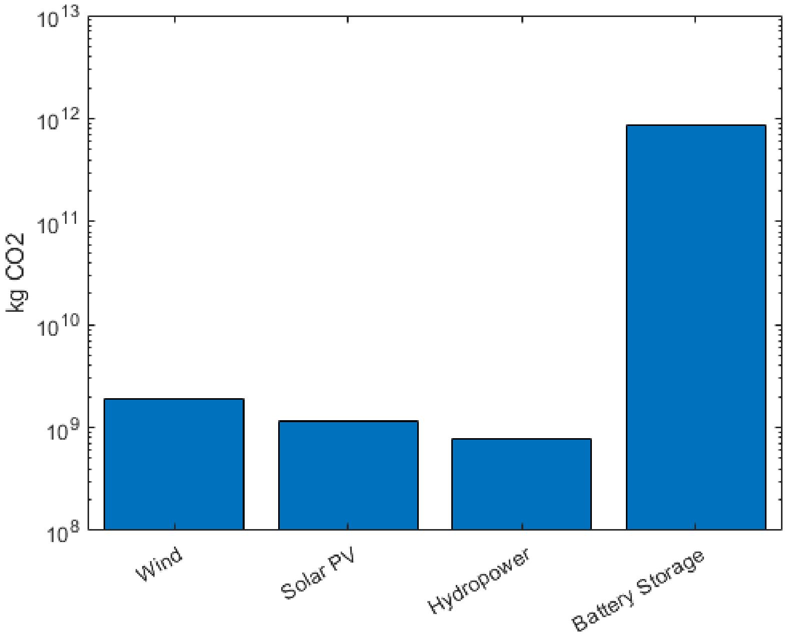

Figure 5.22: CO_2 emissions from each technology in case 4

5.5 Sensitivity analysis

The sensitivity analysis below for the chosen parameters is for case 1. The first table presents a sensitivity analysis with a 50% increase in the input parameters. The second table presents a sensitivity analysis for a decrease of 50% in the input parameters. Note that the learning rate is not included in the original case 1 but added here in order to get a knowledge if the parameter would be sensitive or not. This is followed by a sensitivity analysis regarding environmental impact with the same structure.

Table 5.17 shows the sensitivity analysis for a 50% increase in the input parameters. As can be seen, none of the parameters are sensitive according to the Burgman equation. Despite the conclusion that all parameters are not sensitive, the discount rate proved to induce the largest change in total system cost in comparison to the other parameter changes.

Table 5.17: The table shows a sensitivity analysis with a 50% increase in the input parameters

Input parameters	**Baseline value (x1)**	**New value (x2)**	**Cost of system (billion SEK) (y1)**	**New cost of system (billion SEK) (y2)**	**Sensitivity (absolute value)**
D	5%	7.5%	2396	2973	0.48
VSR	1	1.5	2396	2315	0.07
VWE	1	1.5	2396	2144	0.21
CE	20 000 SEK	30 000 SEK	2396	2406	0.01

D= discount rate[% per year]
L= learning rate [% per year]
For solar PV, wind and hydrogen (i.e., not hydropower)
VSR= Variation Solar Radiation [W/m^2]
VWE= Variation Wind Energy [m/s]
CE= CAPEX of electrolyser [SEK/kW]

Table 5.18 shows the sensitivity analysis for a 50% decrease in the input parameters. None of the parameters except the variation in wind energy are sensitive. The reason for the variation in wind being sensitive is that when the wind energy decreases by 50%, the amount of wind turbines that have the possibility to run at full capacity decreases and it could also be the case that there is an increased amount of hours where the wind speed does not match the cut in speed of the wind turbines. All in all, this means that the wind turbine capacity needs to increase substantially, therefore the cost increases significantly and the sensitivity number exceeds 1.

Table 5.18: The table shows a sensitivity analysis with a 50% decrease in the input parameters

Input parameters	**Baseline value (x1)**	**New value (x2)**	**Cost of system (y1)**	**New cost of system (billion SEK) (y2)**	**Sensitivity (absolute value)**
D	5%	2.5%	2396	1888	0.42
L	1	0.5	2396	1863	0.44
VSR	1	0.5	2396	2636	0.20
VWE	1	0.5	2396	4927	2.11
CE	20 000 SEK	10 000 SEK	2396	2385	0.01

Table 5.19 presents the sensitivity analysis regarding the environmental impact for an increase by 50% in the input parameters for carbon dioxide emissions coming from wind turbines and solar PVs respectively. The parameters show no sensitivity as the sensitivity values are below 1.

Table 5.19: The table shows a sensitivity analysis for the environmental impact with a 50% increase in the input parameters

Input parameter	Baseline value (x1)	New value (x2)	Emissions, Mtonnes (y1)	New emission level, Mtonnes (y2)	Sensitivity (absolute value)
EnvIW	35	53	5.61	7.20	0.55
EnvIS PV	88	132	5.61	6.36	0.27

EnvIW = Wind turbines [g CO2/kWh]
EnvIS = Solar PVs

Table 5.20 shows that none of the parameters are sensitive for a decrease by 50% on the input parameters.

Table 5.20: The table shows a sensitivity analysis for the environmental impact with a 50% decrease in the input parameters

Input parameter	Baseline value (x1)	New value (x2)	Emissions, Mtonnes (y1)	New emission level, Mtonnes (y2)	Sensitivity (absolute value)
EnvIW	35	18	5.61	4.11	0.55
EnvIS PV	88	44	5.61	4.86	0.27

6
Discussion

6.1 Environmental and economic impact

With an increasing welfare, electrification and the possibilities to use batteries and fuel cells in larger scale together with an increasing demand for storage capacity results in an increasing demand for metals (e.g. cobalt, platinum and rare earth metals). With an increasing demand, more and more ore containing metals will be extracted. The ore with the highest concentration of mineable metals can be found in the Earth's crust and more precisely near the surface. When the ores with the highest metal content have been mined, the process goes on to deposits that have less concentration of metal in the ore since the metals are not evenly distributed in the Earth's crust. A high price for metals on the world market would lead to increased incentives to extraction. It is also the case that if the ore contains less metals, more ore needs to be extracted to get the same amount of metal as before. The impact on the environment will increase as the extraction of the ore is an irreversible process where the landscape and the topography is changed forever. Some metals are being recycled in higher rates due to their high economic value. One suggestion here would be to use ecodesign and try to design the products so that dismantling is easy and that the metals can be separated without any impurities from mixing them in order to get a high recycling rate with high quality on the respective metal[46].

Rare earth metals can be found at certain areas around the world with China having the highest production of these elements. These elements are used in applications in the high technology industry, including the renewable energy sector. Since the reserves and production are located to a limited region, there might be a potential risk for tensions and conflicts with restrictions of export quotas. Increasing spending in R&D in order to come up with new materials that could use more abundant materials could be a solution to this[47].

For the wind turbines, one needs to rethink what materials that are used today. Other materials can be used. As an example, the Swedish company Modvion are developing modular towers in laminated timber to use when building wind turbines. As of today, one wind turbine with this technology has been installed outside Gothenburg in research purpose. The advantages with this technique is that it can reduce the carbon emissions since carbon is stored to the timber and does not emit it during the manufacturing process which is not the case with conventional towers that currently are being used when building wind turbines. There is a logistics problem with the transport to the site of these large modules used for the assembly of the tower. In many countries, the maximum base diameter of 4.3 meters will be exceeded on towers with a height of over 100 meters. This means that conventional transportation can not be used. This problem can be solved by using modules that are being put together at the site[48].

6.2 Social aspects

Cobalt is an important component when manufacturing lithium-ion batteries. Around 1/2 to 2/3 of all the cobalt used today comes from the Democratic Republic of the Congo. Child labour is used in the cobalt industry in the Democratic Republic of the Congo. It is also the case that labourers in these mines where they extract the cobalt lack safety equipment and therefore are being exposed to dust that affects their health, including, among others, their respiratory system. The supply chain is complex and the cobalt is being used by multinational companies in Europe, the United States and Asia far away from where it originates[49]. In order to have control over the supply chain and make it traceable, Volvo Cars have started to use block chain technique for the cobalt needed in the batteries for their electrical cars[50]. Another option could be to change to other materials that have a less impact on social injustice and forced labor.

People who live nearby wind power plants may be affected by, among others, noise. The noise consists of mechanical noise coming from the gearbox and the generator. The noise can also consist of aerodynamic noise coming from the rotor blades. The mechanical noise can to a large extent be reduced through the construction process. The aerodynamic noise is more difficult to handle, here it is a trade off between lower noise and less power in the wind turbine. Areas without the background noise from, e.g. traffic will make the noise from the wind turbines be perceived more disturbing[51]. Recent studies have shown that the noise from wind turbines may affect the sleep of people[52].

6.3 Technical aspects

With a system composition of renewable energy sources the system frequency control methods must be adapted to mitigate the risks of frequency deviation from the imbalance between production and load. In Sweden, the frequency of the system must remain at 50 Hz (+/- 0.1) [54]. If the frequency of the system drops below 49 Hz, major disruptions could occur leading to blackouts [54]. There are several methods to mitigate frequency issues by incorporating balancing services in the system, which helps keep the frequency level within the acceptable range of deviation. One such method is the utilisation of the system inertia, in which the energy from the rotation of the generators are connected to the system [55]. However, with an increased integration of renewable energy sources the system inertia will decrease due to the power electronics in wind turbines and solar PVs, which prevent their rotating mass from contributing to the system inertia. As a result, the power system stability decreases and causes difficulties with maintaining operation and control of the power system [55].

Consequentially, reduced system inertia increases the rate of change of frequency during sudden changes within production and load [55]. In order to mitigate the risks of deviating too far from the ideal frequency level of the power system, a fast frequency response is required. One solution is a battery storage system which has a fast response time and may compensate for the production and load variations in the system [55]. Shifting behavioral patterns in consumption and incorporating smart grid solutions may also help with the frequency control and require lower level of storage system, however, due to the intermittent nature of wind and solar in combination with the scale of production from the wind turbines and solar, there may only be a marginal effect on stabilising the system frequency.

In this study, the frequency level of the power system has been discussed but not quantitatively analysed. Therefore there would require further analyses in terms of ancillary services to the power system in order to safeguard the quality of electricity generation in the system and maintain the frequency level within the acceptable limit. Case 4 showed the lowest deviation between load and production due to the high efficiency of the battery storage system, whereas in comparison the integration of a hydrogen storage system required higher production from wind and solar, therefore increasing the level of disparity between production and load in the system. Case 3 showed the highest deviation as a result of omitting hydropower, which serves as a relatively stable source of electricity.

It is also important to consider that this thesis is based on a closed system, meaning that there is no import or export occuring between countries. By incorporating and open system, several factors will be impacted such as the the size of the storage system being reduced. Consequently, investment costs for the storage system will be reduced. With an open system, nearby countries that are interconnected in the energy system can potentially export their overgeneration to countries that aren't generating enough.

6.4 Program structure

The structure of the program in MATLAB was designed to allow flexibility and ease of changing the input parameters for the simulation. In the process file of the program, the size of the increment in calculating the amount of solar panels and wind turbines needed was set to 1000 and 10 respectively, since they were deemed as giving a good balance between accuracy of results and elapsed time. Increasing the increment would yield less accurate results and shorter simulation time, whereas lowering the increment would yield more accurate results at the expense of time.

Another aspect to consider is that the program does not take into account the losses in transmission in the system, which would increase the required total electricity production in order to compensate for the losses. In extension, the increase in production would increase the total cost of the system and CO_2 emissions.

7
Conclusion

From a holistic perspective, the conclusion is that case 1 is a preferable choice for a renewable energy system. Case 1 has the lowest total system cost of 2396 billion SEK. The environmental impact in this case is also the lowest with approximately 5.61 megatonnes of carbon dioxide being emitted annually. Case 4 has a more consistent system frequency than the other cases. The reason for that is the battery storage. One of the disadvantages with the battery storage is that the system will become expensive and have a high environmental impact corresponding to almost 875 megatonnes carbon dioxide per year. One needs to consider that battery technology is developing in a rapid pace so it is likely that the cost and the environmental impact will go down in the future.

In the different cases LCOE for solar PV is higher than the LCOE for wind. This is the case because the solar PV produce much less than what the wind turbines can do in the region.

The total generation from case 3 at 226 TWh was much larger than the other cases, where case 2 had the least difference in comparison with a total generation of 182 TWh. This shows the importance of hydropower to the stability of the power production, which subsequently leads to a reduced size of the storage system. Additionally, in case 3 the system produced no electricity during certain hours, which is the result of the intermittent nature of solar and wind. Hence it is important to incorporate a base-load power plant such as hydropower and integrate an efficient storage system in order to minimise cost and system instability.

The sensitivity analysis showed that the only parameter change that yielded sensitivity according to the Burgman equation was reducing the hourly wind speed data to 50 % of its original value, resulting in a sensitivity value of 2.11 and a total system cost of 4927 BSEK. In comparison, increasing the hourly wind speed data by 50 % of its original value yielded a sensitivity value of 0.21 and a total cost of 2144 BSEK. This shows the effect of the operational range of wind turbines and how vulnerable the system cost is as a result of the weather patterns for wind. The sensitivty value from changing the solar radiation was low (increasing by 50 % yielded 0.07, decreasing by 50% yielded 0.20), which is reasonable as the system composition for solar was set to 10 % of the total generation and the resulting change in total system cost would not be altered significantly as a result.

7.1 Suggestions for future work

For further research within the area, the following suggestions are proposed:

- Look into systems involving other types of technologies for storage and grid stability such as flow batteries and low head pumped hydro.

- Smart grids and how it might affect the usage of electricity with electrical cars being plugged into the grid for charging and as a battery during higher loads.

- Supergrids and what a system like this would look like. Exports and imports between continents and how the supply and the demand could be regulated as the system is scaled up.

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A

Appendix 1

```
% Input Data Parameters

Hour = [1:8760]; % Hours in year
Hour = Hour.'; %Transpose Hour row to column

% Wind

WindSpeed = readtable('WindVingaData.txt'); % Hourly wind speed data
WindDataArray = table2array(WindSpeed); % Convert from table to array

WindDataArray(WindDataArray < 3) = 0; % Cut in speed at 3 m/s
WindDataArray(WindDataArray > 25) = 0; % Cut out speed at 25 m/s

WindDataArray(WindDataArray >= 11 & WindDataArray < 25) = 11 % The turbine produces at maximum capacity at wind speed 11 m/s and maintains level until cut out speed

rw = 60         % Wind swept radius
rho = 1.225       % Air density (ISA Standard)
n = 0.596      % Efficiency of turbine is generally between 35-45 %, using 59.6 % due to Betz Law.

WindHours2 = sum(WindDataArray(:) < 3)
WindHours3 = sum(WindDataArray(:) > 25)
WindHours = 8760 - (WindHours2 + WindHours3) % Calculating amount of hours where the wind turbine produces electricity (between wind speeds 3-25 m/s)

CapacityWindY = 3 % 3 MW

LC = 1 % Learning curve rate

```

```
CfixW = 12800000*LC % CAPEX of installed capacity in SEK/MW

COMw = 148*LC % kr/MWh OPEX costs

r = 0.05 % Discount rate

Tw = 25 % Life expectancy of wind turbine

%%

% Solar PV

SrData = readtable('HGSIGot.txt'); % Hourly solar irradiance
    data
SrDataArray = table2array(SrData); % Convert from table to
    array

SolarHours = sum(SrDataArray > 0) % Amount of hours the
    solar panel produces electricity

A = 5.345 % area of solar PV

PR = 0.75 % Performance ratio of solar PV
gamma = 0.14 % Efficiency of solar PV

CapacitySolarY = 4e-4 % Capacity of solar PV


Cfix = 11280000*LC % CAPEX of installed capacity in SEK/MW

COMs = 141*LC % kr/MWh OPEX costs

T = 25 % Life expectancy of solar PV

SolarPercentage = 0.1 % Percentage of total system
    electricity production that is covered by solar

%%

% Hydropower

HydroData = readtable('HydroDataSwe.txt'); % Hourly
    electricity production from hydropower
HydroDataArray = table2array(HydroData); % Convert from
    table to array

```

```
CapacityHydro = 16300 % Capacity of hydropower

XH = 1 % Factor determining how much of the current
    production hydropower produces in the simulation

CfixH = 22500000 % CAPEX of installed capacity in SEK/MW

COMh = 100 % kr/MWh OPEX costs

Th = 50 % Life expectancy of Hydro power plant


%%

% Storage Batteries

% For batteries (Li-ion)

CAPEXbatt = 2000000 % SEK/MWh
OMbatt = CAPEXbatt*0.04 % OPEX is between 2-4 % of CAPEX

BatEnCap = 2 % Energy capacity of one li-ion battery MWh
LTbatt = 20 % 20 years life expectancy

beta1= 1 % Factor determining amount of overgenerated
    electricity is stored in battery storage (1 = 100%)

%%

% Storage Hydrogen

CAPEXel = 20000000*LC % Capital cost (SEK/MW) for
    electrolyser
CAPEXht = 4380*LC % Capital cost (SEK/kg) for hydrogen tank
CAPEXfc = 6000000*LC % Capital cost (SEK/MW) for fuel cell

OMel = 200000*LC % OM cost (SEK/MW) for electrolyser
OMfc = 0.8*LC % O&G cost (SEK/op.h) for fuel cell

LTel = 15 % Lifetime for electrolyser in years
LTht = 25 % Lifetime for hydrogen tank in years
LTfc = 40000 % Lifetime for fuel cell in operational hours
etael = 0.8 % efficiency of electrolyser
etafc = 0.45 % efficiency of fuelcell

SpecEn =  40 % 40 kWh/kg specific energy of hydrogen
```

```
beta2 = 0 % Total amount of Overgeneration that is stored by
    hydrogen system, 1 = 100%

%%

% System total

ConsumptionTot = readtable('totalconsumption.txt') % Hourly
    consumption data
ConsumptionTotArray = table2array(ConsumptionTot) % convert
    from table to array

%%

% Environmental Impact

EnvIW = 35 % 20-38 g CO2/kWh for wind turbines. Written in
    kg/MWh
EnvIS = 88 % 88 g CO2/kWh for solar panels. Written in kg/
    MWh
EnvIH = 12 % 10-13 g CO2/kWh for hydropower. Written in kg/
    MWh
EnvIB = 100000 % 59000-119000 g CO2/kWh for battery. Written
    in kg/MWh
EnvIHyel = 1552 % 0.0388 kgCo2 per kg H2 electrolysis. 1552
    kg CO2 per MWh
EnvIHyst = 6984 % 0.1746 kgCo2 per kg H2 storage. 6984 kg
    CO2 per MWh
```

B

Appendix 2

```
% Simulation


% Creation of zero matrices
PsolarV = zeros(8760,1);
PwindV = zeros(8760,1);
PhydroV = zeros(8760,1);
PloadV = zeros(8760,1);
PgenV = zeros(8760,1);
PdiffV = zeros(8760,1);
PhydrogenV = zeros(8760,1);
QhydrogenV = zeros(8760,1);
QBattV = zeros(8760,1);
QremainingV = zeros(8760,1);

for time = 1:1:8760
    Psolar = ((A*gamma*SrDataArray(time)*PR)/1000000) %
        Production from one solar PV each hour
    Pwind = (((1/2)*pi*rw.^2*rho*n*WindDataArray(time).^3)
        /1000000) % Production from one wind turbine each hour
    Phydro = HydroDataArray(time)*XH % Hydropower production
        per hour
    Pload = ConsumptionTotArray(time) % Load per hour

    % Results from production per hour stored in matrix
    PsolarV(time) = Psolar
    PwindV(time) = Pwind
    PhydroV(time) = Phydro
    PloadV(time) = Pload

    Pgen = PsolarV(time) + PwindV(time) + PhydroV(time) %
        Aggregated electricity production per hour
    PgenV(time) = Pgen % Results from Pgen stored in matrix

    Pdiff = PgenV(time)-PloadV(time) % Difference between
        generation and load per hour
```

```
    PdiffV(time) = Pdiff % Results from Pdiff stored in
        matrix


   % If loop when generation is larger than load, the
       overgeneration is stored, otherwise it is deemed as
       remaining demand
   if Pdiff > 0
        Qhydrogen = Pdiff*beta2
        Phydrogen = Qhydrogen*etael*etafc*beta2
        QBatt = Pdiff*beta1
        Qremaining = 0
    elseif Pdiff <= 0
        Qhydrogen = 0
        Phydrogen = 0
        QBatt = 0
        Qremaining = Pdiff
   end

   % Results from if loop stored in respective matrices
    QhydrogenV(time) = Qhydrogen
    PhydrogenV(time) = Phydrogen
    QBattV(time) = QBatt
    QremainingV(time) = Qremaining

end

% Summation of values in matrices
PsolarTot = sum(PsolarV)
PwindTot = sum(PwindV)
PhydroTot = sum(PhydroV)
PgenTot = sum(PgenV)
PloadTot = sum(PloadV)
PdiffTot = sum(PdiffV)
PhydrogenTot = sum(PhydrogenV)
QhydrogenTot = sum(QhydrogenV)
QBattTot = sum(QBattV)
QremainingTot = sum(QremainingV)

% System check if the stored electricity can cover the
    remaining demand
RemainingStorage = PhydrogenTot+QBattTot-abs(QremainingTot)

if RemainingStorage >= 0
     return
end
```

```
HydroPercentage = PhydroTot/((abs(QremainingTot)/(etael*etafc))+PgenTot) % Percentage of total electricity production covered by hydropower
WindPercentage = 1-HydroPercentage-SolarPercentage % Percentage of total electricity production covered by wind turbines


%%

% For loop to calculate a factor X of how many wind turbines and solar
% PVs required to ensure that the stored electricity covers the demand
% during hours of undergeneration
for X = 1:10:inf
     PsolarZ = X.*PsolarV
     PwindZ = X.*PwindV
     PGenZ = PsolarZ+PwindZ+PhydroV
     A1 = PGenZ(PGenZ>PloadV)
     A2 = PloadV(PloadV<PGenZ)
     A3 = PGenZ(PGenZ<PloadV)
     A4 = PloadV(PloadV>PGenZ)
          if (((sum(A1)-sum(A2))*etael*etafc)*beta2)+(sum(A1)-sum(A2)*beta1)>=sum(A4)-sum(A3)
             return
          end
end

A6 = sum(A1)-sum(A2)
A7 = sum(A4)-sum(A3)

%%

% Conversion of factor X to amount of solar PVs required to produce the
% desired solar percentage of total production
for XS1 = 1:1000:inf
     PsolarJ = XS1.*PsolarV
     if sum(PsolarJ)>=SolarPercentage*sum(PGenZ)
         return
     end
end
```

```
%%

% Conversion of factor X to amount of wind turbines required to produce the
% remaining production that is not covered by solar or hydro

WindPercentageJ = 1-(sum(PsolarJ)+sum(PhydroV))/sum(PGenZ)

for XW1 = 10:10:inf
    PwindJ = XW1.*PwindV
    if sum(PwindJ)>=WindPercentageJ*sum(PGenZ)
        return
    end
end

%%

% Same loop as the beginning of the simulation with the calculated amount
% of solar PV and wind turbines needed to satisfy demand
PsolarY = XS1.*PsolarV
PwindY = XW1.*PwindV
PGenY = PsolarY+PwindY+PhydroV

PdiffY = PGenY-PloadV

QhydrogenY2=zeros(8760,1);
PhydrogenY2=zeros(8760,1);
QBattY2=zeros(8760,1);
QremainingY2=zeros(8760,1);

for time = 1:1:8760

 if PdiffY(time) > 0
        QhydrogenY = PdiffY(time)*beta2
        PhydrogenY = QhydrogenY*etael*etafc*beta2
        QBattY = PdiffY(time)*beta1
        QremainingY = 0
    elseif PdiffY(time) <= 0
        QhydrogenY = 0
        PhydrogenY = 0
        QBattY = 0
        QremainingY = PdiffY(time)
end

```

```
 QhydrogenY2(time) = QhydrogenY
 PhydrogenY2(time) = PhydrogenY
 QBattY2(time) = QBattY
 QremainingY2(time) = QremainingY

end

PsolarTotY = sum(PsolarY)
PwindTotY = sum(PwindY)

PGenTotY = sum(PGenY)
PdiffTotY = sum(PdiffY)
PhydrogenTotY = sum(PhydrogenY2)
QhydrogenTotY = sum(QhydrogenY2)
QBattTotY = sum(QBattY2)
QremainingTotY = sum(QremainingY2)

RemainingStorageY = PhydrogenTotY+QBattTotY-abs(
   QremainingTotY)


B1 = PGenY(PGenY>PloadV)
B2 = PloadV(PloadV<PGenY)
B3 = PGenY(PGenY<PloadV)
B4 = PloadV(PloadV>PGenY)
B5 = sum(B1)-sum(B2) % Total overgeneration
B6 = sum(B4)-sum(B3) % Total demand remaining

TimeProduction = sum(PdiffY < 0) % Amount of hours where the
    storage systems deliver electricity back to the system
TimeStorage = sum(PdiffY >= 0) % Amount of hours where the
   excess electricity is stored in the storage systems


%%
% System balance

CapacityWind = PwindTotY/WindHours % Minimum capacity
   required
CapacityWindYTot = CapacityWindY*XW1 % Total capacity based
   on capacity of wind turbine used in input parameter
CFw = (PwindTotY)/(CapacityWindYTot*8760) % Capacity factor
   of the wind turbines

```

```
CapacitySolar = PsolarTotY/SolarHours % Minimum capacity required
CapacitySolarYTot = CapacitySolarY*XS1 % Total capacity based on capacity of solar PV used in input parameter
CFs = PsolarTotY/(CapacitySolarYTot*8760) % Capacity factor of solar PVs

CFh = PhydroTot/(8760*CapacityHydro) % Capacity factor of hydropower

% Check that the percentage of total generation corresponds to input data
% (may have slight deviation depending on size of increments in for loops)
SolarComp = PsolarTotY/PGenTotY
WindComp = PwindTotY/PGenTotY
HydroComp = PhydroTot/PGenTotY


% Cost of system


% Wind
AFCw = (CfixW*CapacityWindYTot*r*(1+r)^Tw)/((1+r)^Tw-1) % Annualised fixed cost per year. (SEK/year)
TotFixCostw = AFCw*Tw % Total fixed cost over lifetime(SEK)
OPEXw = COMw*PwindTotY % Annualised operational cost (SEK/year)
OPEXwtot = OPEXw*Tw % Total operational cost over lifetime (SEK)
syms x % In order to define variable x
F2 = symsum((1+r)^-x,x,1,Tw)
F2=double(F2) % Why this works I do not know but it helps with the crazy fraction
LCOEw = ((CfixW*CapacityWindYTot + F2*COMw*(PwindTotY))/(F2*PwindTotY))/(1000) % STEwT to get total operating cost for one 3 MW wind turbine
% producing STEwT for one year. Divide by 1000 to get SEK/kWh)


% Solar
AFCs = (Cfix*CapacitySolarYTot*r*(1+r)^T)/((1+r)^T-1) % Annualised fixed cost per year. (SEK/year)
TotFixCosts = AFCs*T % Total fixed cost over lifetime(SEK)
OPEXs = COMs*PsolarTotY; % Annualised operational cost (SEK/
```

```
year)
OPEXstot = OPEXs*T % Total operational cost over lifetime (SEK)

syms y % In order to define variable y
F1 = symsum((1+r)^-y,y,1,T)
F1=double(F1)
LCOEs = ((Cfix*CapacitySolarYTot + F1*COMs*PsolarTotY)/(F1*PsolarTotY))/(1000) % LCOE in (SEK/kWh)


% Hydro
AFCh = (CfixH*CapacityHydro*r*(1+r)^Th)/((1+r)^Th-1) % Annualised fixed cost per year. (SEK/year)
TotFixCosth = AFCh*Th % Total fixed cost over lifetime(SEK)

OPEXh = COMh*PhydroTot % Annualised operational cost (SEK/year)
OPEXhtot = OPEXh*Th % Total operational cost over lifetime (SEK)

syms z % In order to define variable z
F3 = symsum((1+r)^-z,z,1,Th)
F3=double(F3)
LCOEh = ((CfixH*12600 + F3*COMh*PhydroTot)/(F3*PhydroTot))/(1000) % % LCOE in (SEK/kWh)


% Hydrogen
LTfcY = LTfc/TimeProduction % Amount of hours the fuel cell is active

CAPEXelTot = (((QhydrogenTotY)/(TimeStorage))*CAPEXel) % CAPEX (SEK)
OMelTot = (((QhydrogenTotY)/(TimeStorage))*OMel) % Annualised operational cost (SEK/year)
OPEXhydeltot = OMelTot*LTel % Total operational cost over lifetime (SEK)

CAPEXhtTot = (CAPEXht*(1/SpecEn)*QhydrogenTotY*etael) % CAPEX (SEK) % Multiply by electrolyser efficiency since we will only store 80% of the hydrogen
% the electrolyser is theoretically capable of producing.

CAPEXfcTot = CAPEXfc*((QhydrogenTotY*etael)/(TimeProduction)); % CAPEX (SEK)
```

```
OMfcTot = OMfc*TimeProduction % Annualised operational cost (SEK/year)
OPEXhydfctot = OMfcTot*LTfcY % Total operational cost over lifetime (SEK)

CAPEXhydTot = CAPEXelTot + CAPEXhtTot + CAPEXfcTot; % Total CAPEX of hydrogen system (SEK)
OPEXhyd = OMelTot + OMfcTot; % Annualised operational cost of hydrogen storage system (SEK/year)
OPEXhydtot = OPEXhydeltot + OPEXhydfctot % Total operational cost of hydrogen storage system (SEK)

AFChydel = (CAPEXelTot*r*(1+r)^LTel)/((1+r)^LTel-1) % Annualised fixed cost per year. (SEK/year)
AFChydht = (CAPEXhtTot*r*(1+r)^LTht)/((1+r)^LTht-1) % Annualised fixed cost per year. (SEK/year)
AFChydfc = (CAPEXfcTot*r*(1+r)^LTfcY)/((1+r)^LTfcY-1) % Annualised fixed cost per year. (SEK/year)
AFChydrogen = AFChydel + AFChydht + AFChydfc % Annualised fixed cost per year of total hydrogen storage system. (SEK/year)

TotFixCosthydel = AFChydel*LTel % Total fixed cost over lifetime(SEK)
TotFixCosthydht = AFChydht*LTht % Total fixed cost over lifetime(SEK)
TotFixCosthydfc = AFChydfc*LTfcY % Total fixed cost over lifetime(SEK)
TotFixCosthyd = TotFixCosthydel + TotFixCosthydht + TotFixCosthydfc % Total fixed cost of hydrogen storage system (SEK)

syms v % In order to define variable v
F5 = symsum((1+r)^-v,v,1,LTel)
F5=double(F5)
LCOEhydrogen = ((CAPEXhydTot+F5*OPEXhydtot)/(F5*QhydrogenTotY*etael*etafc))/(1000) % LCOE in (SEK/kWh)


% Battery
CAPEXbattTot = CAPEXbatt*QBattTotY % CAPEX (SEK)

AFCbatt = (CAPEXbattTot*r*(1+r)^LTbatt)/((1+r)^LTbatt-1) % Annualised fixed cost per year. (SEK/year)

TotFixCostBatt = AFCbatt*LTbatt % Total fixed cost over
```

```
    lifetime(SEK)

OPEXbatt = OMbatt*QBattTotY % Annualised operational cost (
    SEK/year)
OPEXbatttot = OPEXbatt*LTbatt % Total operational cost over
    lifetime (SEK)

syms w % In order to define variable w
F4 = symsum((1+r)^-w,w,1,LTbatt)
F4=double(F4)
LCOEbatt = ((CAPEXbattTot+F4*OPEXbatttot)/(F4*QBattTotY))
    /(1000) % LCOE in (SEK/kWh)


% System
AFCTotSystemCost = AFCh + AFCbatt + AFChydrogen + AFCs +
    AFCw; % AFC for total system (SEK)
TotFixSystemCost = TotFixCosth + TotFixCosts + TotFixCostw +
     TotFixCostBatt +TotFixCosthyd % Total fixed cost for
    total system(SEK)



OPEXsystem = OPEXh + OPEXs + OPEXw + OPEXbatt + OPEXhyd %
    Annualised operational cost for total system (SEK/year)
TotOPEXsystem = OPEXhtot + OPEXstot + OPEXwtot + OPEXbatttot
     + OPEXhydtot % Total operational cost for total system (
    SEK)

TotSystemCost = TotFixSystemCost + TotOPEXsystem; % Total
    cost of system (SEK)


% Environmental impacts
TEnvIW = (EnvIW*PwindTotY) % Wind (kg CO2)
TEnvIS = (EnvIS*PsolarTotY) % Solar (kg CO2)
TEnvIH = (EnvIH*PhydroTot) % Hydro (kg CO2)
TEnvIB = (EnvIB*QBattTotY) % Battery (kg CO2)
TEnvIHyel = (EnvIHyel*QhydrogenTotY) % Electrolyser (kg CO2)
TEnvIHyst = (EnvIHyst*QhydrogenTotY*etael) % Hydrogen
    storage tank (kg CO2)
TEnvIHydr = TEnvIHyel + TEnvIHyst % Total CO2 emissions from
     hydrogen storage system (kg CO2)

TEnvImpact = TEnvIW+TEnvIS+TEnvIH+TEnvIB+TEnvIHydr % Total
    CO2 emissions from system (kg CO2)
```

```
TEnvImpactPMWh = TEnvImpact/(PGenTotY) % Total CO2 emissions from system per MWh (kg CO2/MWh)
```

C

Appendix 3

```
% Visualisation of results

% Wind

plot(Hour,PwindY)
hold on
plot(Hour,PloadV)
xlim([1 8760])
title('Annual production and consumption Wind')
xlabel('Hour')
ylabel('MWh')
legend('Production', 'Consumption')
hold off

%%


% Solar PV

plot(Hour,PsolarY)
hold on
plot(Hour,PloadV)
xlim([1 8760])
title('Annual production and consumption Solar')
xlabel('Hour')
ylabel('MWh')
legend('Production', 'Consumption')
hold off

%%

% Hydropower

plot(Hour,PhydroV)
hold on
plot(Hour,PloadV)
```

```
xlim([1 8760])
title('Annual production and consumption Hydropower')
xlabel('Hour')
ylabel('MWh')
legend('Production', 'Consumption')
hold off

%%

% Electricity delivered back to the system from hydrogen
    storage system

plot(Hour,PhydrogenY2)
hold on
plot(Hour,PloadV)
xlim([1 8760])
title('Annual hydrogen elprod and consumption')
xlabel('Hour')
ylabel('MWh')
legend('Hydrogen Storage Production', 'Consumption')
hold off

%%

% Electricity stored from the system by hydrogen storage
    system

plot(Hour,QhydrogenY2)
hold on
plot(Hour,PloadV)
xlim([1 8760])
title('Annual hydrogen storage and consumption')
xlabel('Hour')
ylabel('MWh')
legend('Hydrogen Storage', 'Consumption')
hold off

%%

% Electricity stored from the system by battery storage
    system

plot(Hour,QBattY2)
hold on
plot(Hour,PloadV)
xlim([1 8760])
```

```
title('Annual battery storage and consumption')
xlabel('Hour')
ylabel('MWh')
legend('Battery Storage', 'Consumption')
hold off
%%

% Total system


plot(Hour,PGenY)
hold on
plot(Hour,PloadV)
xlim([1 8760])
title('Total annual production and consumption');
xlabel('Hour')
ylabel('MWh')
legend('Production', 'Consumption')
hold off

%%

% System total load duration curve

PGenYDesc = sort(PGenY,'descend')

plot(Hour,PGenYDesc)
hold on
xlim([1 8760])
title('Load duration curve for total system production');
xlabel('Hour')
ylabel('MWh')
legend('Production')
hold off


%%


% CO2 emissions

EnvX = categorical({'Wind','Solar PV','Hydropower','Hydrogen Storage','Battery Storage'});
EnvX = reordercats(EnvX,{'Wind','Solar PV','Hydropower','Hydrogen Storage','Battery Storage'});
EnvY = [TEnvIW TEnvIS TEnvIH TEnvIHydr TEnvIB];
```

```
bar(EnvX,EnvY)
ylim([10^8 10^13])
set(gca,'YScale', 'log')
title('CO2 Emissions');
ylabel('kg CO2')
```