Lappeenranta-Lahti University of Technology LUT
LUT School of Energy Systems
Degree Programme in Environmental Technology
Bachelor's thesis

ASSESSMENT OF A RENEWABLE ENERGY SYSTEM FOR LONGYEARBYEN IN 2030

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ABSTRACT

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To obtain the targets to halt global warming, a transition to renewable energy systems is crucial. Longyearbyen is an Arctic settlement on the Svalbard archipelago and currently Longyearbyen’s energy system is based on locally mined coal and imported diesel as a reserve source. The existing power plant is aging and there is uncertainty of how long the coal resources will last. Thus, new solutions for the energy system are needed. In this Bachelor’s thesis, a 100 % renewable energy system for Longyearbyen in 2030 is modelled with a modelling tool EnergyPLAN. In addition to the current system, two scenarios with different heat and electricity demands for the future system are modelled. In the *2030* scenario, 6.9 MW onshore wind, 16 MW offshore wind and 3.03 MW solar PV are needed. In the *2030 Lower demands* scenario, the numbers are 10.35 MW, 8 MW and 7.49 MW, respectively. The results show that a renewable energy system for Longyearbyen is technically feasible. The costs of the renewable systems are higher than the current system, but investment and maintenance costs also stand for local jobs. In addition, if the costs of the CO_2 emissions were included, the differences in the costs would be even smaller.

CONTENTS

ABBREVIATIONS

a	year
BTES	Borehole thermal energy storage
CF	Capacity factor
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
e	Electric units
EU ETS	EU Emissions trading system
G	Giga
GWh	Gigawatt hour
gas	Gas units
H_2	Hydrogen
k	Kilo
M	Mega
MWh	Megawatt hour
M€	Million euros
PV	Photovoltaics
P2G	Power-to-gas
P2H	Power-to-hydrogen
V2G	Vehicle-to-grid

1 INTRODUCTION

The transition to renewable energy is essential to curb on-going climate change. In the Paris Agreement in 2015, 175 parties agreed to aim to limit the warming below 2 °C and pursuing below 1.5 °C compared to pre-industrial levels (United Nations 2015). Reaching 1.5 °C would already cause severe consequences. However, the impacts on, for example, sea level or biodiversity are lower in 1.5 °C warming compared to 2 °C warming. To stay below 1.5 °C, global net CO_2 emissions should decline 45 % by 2030 and by 2050 the world should reach net zero emissions (IPCC 2018). Since two-thirds of the global greenhouse gas emissions result from the energy sector, the energy and power production based on fossil fuel-free solutions are needed (IRENA 2019). Reducing the emissions from energy production is inevitable also in remote settlements, for example in the Arctic. The transition to renewable energy-based systems has also economic reasons when the system is not fully dependent on the changing prices of fossil fuels or imported energy. The security of the system can thus be improved as well, which is important especially for the remote settlements.

Longyearbyen is an Arctic settlement on the Svalbard archipelago located at 78°13’N and 15°38’E and is one of the northernmost inhabited places (Fig. 1). In September 2020, the population of Longyearbyen and the research centre Ny-Ålesund was 2417 (Statistics Norway 2020). Longyearbyen was founded in 1906 for coal mining, but the mining industry has decreased during the past years. At the moment, Mine 7 in Longyearbyen is the only running Norwegian coal mine and employs around 40 people (Store Norske 2020). Mine 7 provides the major energy source for the local power plant, Energiverket. Nowadays, the main industry in Longyearbyen is tourism and culture. The tourism industry is growing and especially the number of cruise tourists has increased during the past years. The main tourist seasons on the island are spring and summer. Besides the tourism, manufacturing, construction and transport and research and education are the biggest industries. (Statistics Norway 2017.)

Transitioning the energy systems to one that is renewable based has special challenges in the Arctic due to the harsh climate. Measured at the Svalbard Airport from 1971 until 2000, the mean winter temperature has been -13.9 °C and the mean summer temperature 4.5 °C. The coldest month is usually February, while the warmest is July. (Hanssen-Bauer et al. 2019.) On the coldest days, the temperature can drop well below -30 °C (Norsk Klimaservicesenter 2020). In Longyearbyen, the amount of sunlight changes drastically from winter to summer. The polar night lasts from the late October until the mid-February. During this time there is no sunlight available and this limits the use of solar energy only to part of the year. The polar day occurs from late April until late August and at that time the sun does not set. High wind speeds and stormy weather are common during winter. Measured at Svalbard Airport from 1975 till 2000, Longyearbyen has annually on average 51 days where the maximum wind speed is strong breeze (10.8 ms^{-1}) or stronger (Hanssen-Bauer et al. 2019).

The Arctic region is particularly sensitive to climate change. In recent decades, the warming trend in the Arctic has been twice as large as the global average. The temperature change is greater near the poles than in the mid-latitudes and this phenomenon is called the Arctic Amplification. From 1971 to 2017, the mean annual temperature in Svalbard has increased by 3-5 °C. Especially winter temperatures are increasing which has severe consequences to, for instance, the sensitive Arctic ecosystem. (Hanssen-Bauer et al. 2019.) Norway's target is to reduce emissions 50-55 % by 2030 from 1990 levels. Norway aims to take a leading role in climate actions. Therefore, there is political pressure to shut down the coal industry and transitioning Longyearbyen's energy system towards a more climate neutral one. (Ministry of Climate and Environment 2020.) Longyearbyen's power plant emits approximately 70 000 tons of CO_2 annually (Longyearbyen Lokalstyre 2019). Based on the population in 2020, the CO_2 emissions per capita are around 29 tons. For comparison, in the whole of Norway, the number is 9.43 tons, and in the USA 16.14 tons (Knoema 2020).

The aim of this Bachelor's thesis is to create a 100 % renewable energy system for Longyearbyen in 2030 with a modelling tool EnergyPLAN and obtain an overview of the needed installed capacities and the costs. The future system has to be based on renewable energy sources, secure and cost-effective. In the modelling, the electricity and heat demands are included. The transport fuel data were not available and thus the transport sector is not included in this study.

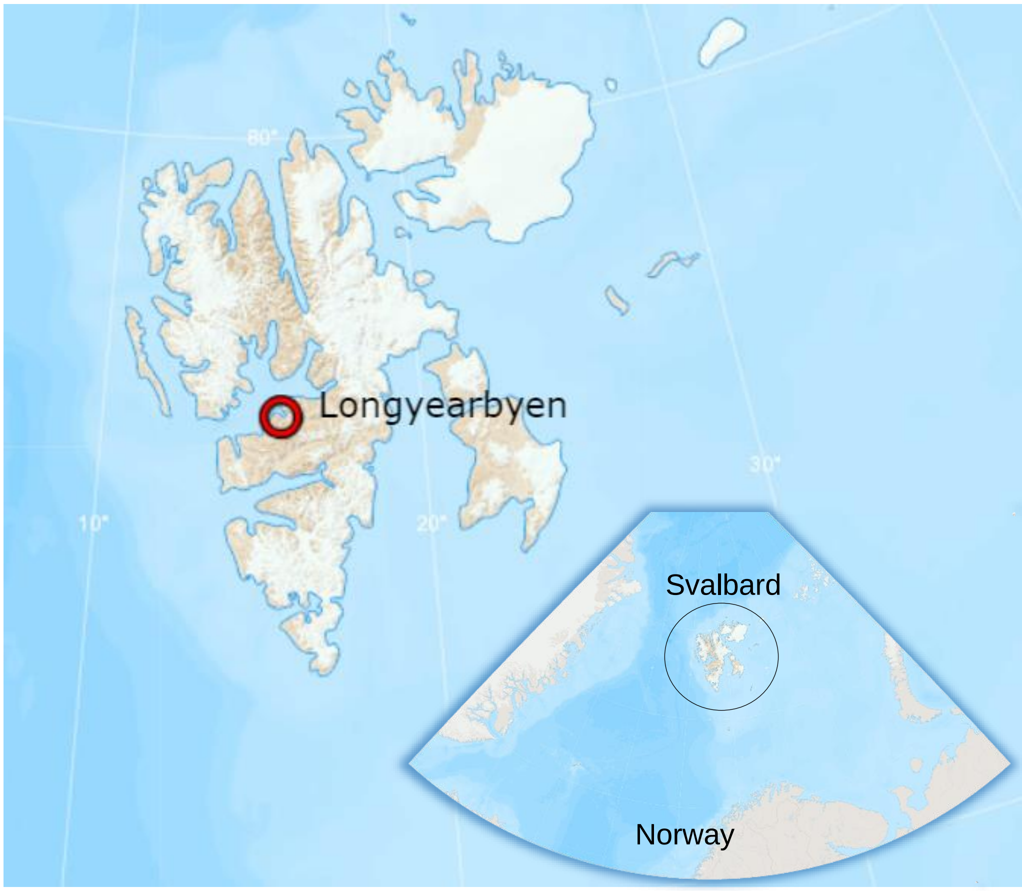

Figure 1. A map of Svalbard (Norwegian Polar Institute 2020).

2 LONGYEARBYEN’S CURRENT ENERGY SYSTEM

The current energy system in Longyearbyen is based on coal and diesel. Energiverket – is a combined heat and power (CHP) power plant that was built in 1982. Energiverket produces around 70 GWh heat and 40 GWh electricity annually using 25-29 000 tons of coal. There are two steam turbines running on coal. Turbine 1 is used to produce both electricity and district heat, while Turbine 2 only produces electricity. For the peak electricity demand, there are also five diesel generators, one of them located close to the University Centre in Svalbard. For the peak heat demand, there is one diesel-fired boiler at the power plant and along the district heat network there are six diesel-fired boilers, “Fyrhusene”. In Table 1, the capacities and efficiencies of the different units are seen. (Tennbakk et al. 2018.)

The power plant’s design temperature is -40 °C. The cold climate means that the buildings need to be heated the year round. The heat produced at the power plant is mainly used by the households and the municipal services for space heating, heating ventilation air and tap water. Around 70 % of the district heat production follows the outdoor temperature. The district heating pipes are also used to warm the water and sewer pipes to prevent freezing. Electricity is mainly consumed in the industrial sector. Energiverket itself consumes 17 % of the total electricity production, mainly because of its treatment plant. The other significant consumers are Mine 7 and the satellite station SvalSat consuming 13 % and 10 % of the electricity, respectively. The power plant could be used even until 2038 even though the maintenance costs would increase considerably, which among other things urge the change of the current energy system. There is also uncertainty of the sufficiency of the coal reserves. The estimate is that it will last until 2025. (Tennbakk et al. 2018.)

Longyearbyen’s energy system is therefore mainly run on coal with diesel as a reserve resource. However, there is some renewable energy in use. For example, there has been solar panels installed on the facade of Svalbard Airport in total 138 kW (Longyearbyen Lokalstyre

2019). The produced energy represents 10 % of the airport's electricity consumption (SunPower 2019). Also, some residential buildings have solar panels. Nevertheless, this is an extremely small part of the electricity production, but shows that there is potential and will to use renewable energy in the Arctic.

Table 1. Electricity and heat production at Energiverket (Tennbakk et al. 2018).

Station	Source of energy	Capacity, electricity [MW]	Capacity, district heat [MW]	Efficiency, electricity production	Efficiency, heat production
Energiverket	Coal	7.5	14	Turbine 1: 19 % Turbine 2: 27 %	Turbine 1: 63 %
Energiverket and UNIS	Diesel	8.9	5		
Fyrhusene	Diesel		15.7		

3 RENEWABLE ENERGY RESOURCES

Transitioning the energy system to one that is renewable based has special challenges in Longyearbyen due to the cold climate, polar night, and remote location. According to previous studies made, there is potential in renewable energy in the Arctic and Longyearbyen. In this section, possible alternative energy resources are presented.

Wind and solar photovoltaics (PV) are often seen as cornerstones of renewable energy systems. The wind speeds in Svalbard are high, especially in winter. The solar resources are good in summer. During the polar night, solar power is not applicable. Ringkjøb et al. (2020) showed in their 100 % renewable *"Isolated system"* -scenario that large capacities of wind and solar are needed for an isolated system in Longyearbyen. The onshore wind and solar capacity in this case in 2030 are modelled to be 126 MW and 119 MW, respectively, with hydrogen and batteries as a storage system. Allowing hydrogen import, the "*HYD"* scenario requires 18 MW onshore wind and 6 MW solar PV capacity. (Ringkjøb et al. 2020.) Also, Tennbakk et al. (2018) stated that wind and solar are the most realistic local renewable energy resources. The scenario with around 50 % of renewables gave capacities of 25.2 MW wind and 25 MW solar, and in the scenario with 80 % of renewables the numbers were 63 MW and 25 MW, respectively. (Tennbakk et al. 2018.)

However, in wind power, there are several uncertainties regarding, for example, the icing and the effects of the wind turbines on the environment and landscape. Tennbakk et al. (2018) did not take offshore wind into account due to the environmental impacts and higher costs. In Tennbakk et al. (2018) and Ringkjøb et al. (2020) they have used the mountain Platåberget as the location for the onshore turbines. Tennbakk et al. (2018) have stated reasons to place wind turbines there and, among other things, the already existing roads and power cables support the location. However, Kongsberg Satellite Services (KSAT), the company operating the satellites on Platåberget, has deduced that the turbines would affect the operation of satellites. The solar panels are either placed on Platåberget to represent a solar park or on rooftops. The possible rooftop area for solar panels is 151 000 m^2. The uncertainties regarding the solar panels are related to the possible snow accumulation on the panels. (Tennbakk et al. 2018.)

Geothermal energy could be a possible energy source in Longyearbyen. The temperature measurements from the exploration boreholes showed higher geothermal potential in Svalbard compared to mainland Norway. (Midttømme et al. 2015.) Thus, geothermal energy could be used for both the heat and electricity generation. Tennbakk et al. (2018) have stated that there are remarkable uncertainties in geothermal energy in Longyearbyen regarding the technology, deep drills, and costs. Hence, as the main heating system its feasibility must be considered. In this study, geothermal energy is included in terms of utilizing ground source heat pumps in addition to a CHP plant.

Currently, all the waste produced in Longyearbyen is transported to mainland Norway to be recycled there (Tennbakk et al. 2018). According to an assessment made in 2014 of the waste incineration plant in Longyearbyen, the total amount of waste is 1220 tons per year. It consists of 7 % paper, 20 % wood and 73 % combustible waste, which includes plastic but not organic waste. The calorific value is estimated to be 3.6 kWh/kg. Burning the waste could provide a part of the heat production. However, due to the small amount of waste, technological and economic reasons, and the uncertainty of fulfilling the emission regulations, Norconsult came to the conclusion that building a waste incineration plant in Longyearbyen is not recommendable. (Norconsult 2014.) Hence, waste as a source of energy or biogas has not been taken into account in this study. There are also several other common renewable energy technologies that cannot be utilized in Svalbard. For example, there are no biomass resources in Svalbard and the use of hydropower or seawater-based heat pumps would not be feasible due to the lack of potential and the cold climate.

Producing hydrogen from renewable electricity through electrolysis, in a process called Power-to-Hydrogen (P2H), is an important technology in renewable energy systems. An electrolyser splits water into hydrogen and oxygen, and hydrogen can then be stored and converted back into electricity when needed. It can also be converted into synthetic fuels or used in fuel cell vehicles. In addition to power and transport sectors, it is possible to use hydrogen to produce heat for residential or industrial purposes. P2H also reduces the curtailment from the renewable sources since the excess electricity can be used in the P2H process. (IRENA 2019.) Hydrogen solutions have already begun to be investigated in

Svalbard. The coal company Store Norske has started a project in transitioning Isfjord Radio, an old radio station and a current tourist attraction, into a renewable energy system. The plan is to use locally produced wind and solar PV with batteries, thermal storage, and hydrogen by 2023. (Store Norske 2020.) It has also been proposed that hydrogen could be imported from mainland Norway. Hydrogen could be produced in Finnmark, in the north of Norway, from wind power. The hydrogen would be bound in ammonia and then transported to Longyearbyen, where it would be used in fuel cells and gas turbines. (Statkraft 2018.) Ammonia could also be used as a transport fuel in fuel cell vehicles.

In the systems that are heavily dependent on renewable energy resources, different electricity storage options are needed to balance the times when fluctuating wind and solar resources are high or low. Hydrogen storage can be used as a long-term (seasonal) storage, while batteries are usually better for short-term storage (IRENA 2019). Currently, lithium-ion batteries are the most widely used batteries. The costs of batteries have been relatively high, but when the installed capacities have increased, the costs have decreased gradually. In an electrified transport sector, batteries play a big role. At the moment, pumped hydro storage is still the most used storage system globally. However, this is not seen as an option for Longyearbyen. (IRENA 2017.) For thermal storage, there have been plans to build a test site for investigating borehole thermal energy storage (BTES) in Longyearbyen that could work as a seasonal energy storage.

An option that has also been proposed is an electric cable from mainland Norway. In Tennbakk et al, this solution has been assessed. A cable from Finnmark to Longyearbyen with a length of 930 km would be the world’s longest subsea power cable. This solution would be remarkably more costly compared to the other solutions. Also, environmental impacts during the construction and operation are suspected to be high. (Tennbakk et al. 2018.)

4 DATA AND METHODS

In this section it is described how the data have been processed for the modelling. In the modelling, the year 2018 is used as a reference year, so the data from that year are used. The year 2018 was chosen for the energy demand data were the most reliable and current.

4.1 Wind data

The onshore wind turbines are assumed to be placed on Gruvefjellet, a mountain in Longyearbyen with a height of 464 m above sea level. As mentioned in Section 3, the previous studies have used Platåberget as the location for the onshore turbines. In addition to the uncertainties of the possible effects on satellites, the wind data on Platåberget began to be measured on the 3rd of February in 2018, so more than 744 data points are missing. For these reasons, the location was chosen to be Gruvefjellet, a mountain with a similar height and wind conditions to Platåberget. The wind speeds from Gruvefjellet are retrieved from the weather station monitored by the University Centre in Svalbard (The University Centre in Svalbard 2020). The offshore wind turbines are assumed to be placed in Isfjorden, the largest fjord of Svalbard. Since there are no offshore wind data, the wind speeds from Isfjord Radio are used (Norsk Klimaservicesenter 2020). This location is rather far from Longyearbyen and not seen as a reasonable site for the electricity production for Longyearbyen. The wind conditions may vary from the locations more inside the fjord. However, the location is chosen to represent the offshore winds in Isfjorden. The map of the data points is seen in Fig. 2.

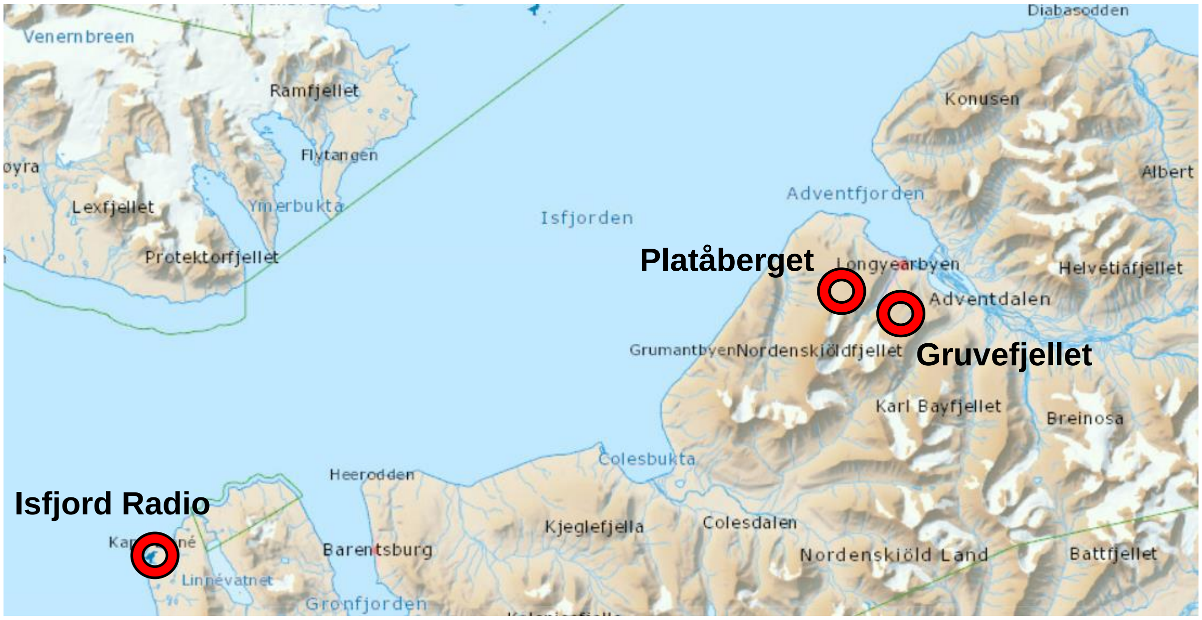

Figure 2. The locations of the wind and solar data points. Isfjord Radio is used for the offshore wind and Gruvefjellet for the onshore wind. Platåberget is used for the solar radiation data point. (Norwegian Polar Institute 2020.)

The onshore turbines are assumed to be Vestas V136-3.45 MW turbines and the offshore Vestas V164-8.0 MW turbines. The wind speeds are measured at 10 m height and thus the wind speeds at the hub heights are calculated by:

$$\frac{U(z)}{U_{ref}} = \frac{log\left(\frac{H}{z_0}\right)}{log\left(\frac{H_{ref}}{z_0}\right)}, \tag{1}$$

where $U(z)$ is the wind speed at the hub height, U_{ref} the wind speed at 10 m, H the hub height, H_{ref} 10m and z_0 is the roughness length. The hub height of 112 m is used for Vestas V136-3.45 MW and 105 m for Vestas V164-8.0 MW (Wind Turbine Models 2020). The roughness length of 0.002 m is used for both the winds. When using the logarithmic wind profile, the atmosphere is assumed to be neutral. (Wallace & Hobbs 2006.)

The power curves of the turbines are used to create the hourly wind distribution profile needed for modelling (Wind Turbine Models 2020). The power values at each wind speed are calculated at every 0.25 ms^{-1}. Since the power curve resolutions are either 0.5 or 1.0 ms^{-1}, a linear interpolation has been made. With the hourly wind speeds and the power curves, the hourly wind energy production is created. Each value is then divided by the maximum output (3.45 MW for the onshore and 8.0 MW for the offshore turbine) to get a distribution varying from 0 to 1. A capacity factor *CF* is calculated as a relation between the actual energy production to the optimal energy production:

$$CF = \frac{P_{actual}}{P_{max} * 8784\ h}, \tag{2}$$

where P_{actual} is the calculated power output with the measured wind speeds from 2018, P_{max} is the maximum output (3.45 MW for the onshore and 8.0 MW for the offshore) and 8784 h are the hours in a leap year. The hourly production values give annual capacity factors of 28 % for the onshore turbine and 47 % for the offshore turbine. The full load hours for onshore and offshore turbines are 2452 h and 4107 h, respectively. In offshore wind, the wind turbine would have to be shut off for 14 hours due to too high wind speeds (over 25 ms^{-1}), and in onshore wind for two hours (over 22.5 ms^{-1}).

4.2 Solar data

To calculate the solar power production, the solar radiation data measured on Platåberget in 2018 are used. The parameter used is an hourly mean global radiation, which is the downward shortwave radiation from the sun and is measured on a horizontal surface. The measurements on Platåberget have started on the 3rd of February in 2018. The global radiation is mainly 0 before that due to the polar night except some hours approximately between 27th of January and 3rd of February. The missing values from that time are replaced with 2019 data. Also, this time is not important for the solar power production and thus, the created distribution is regarded as representative. The global radiation in 2018 is seen in Fig. 3 (Norsk Klimaservicesenter 2020).

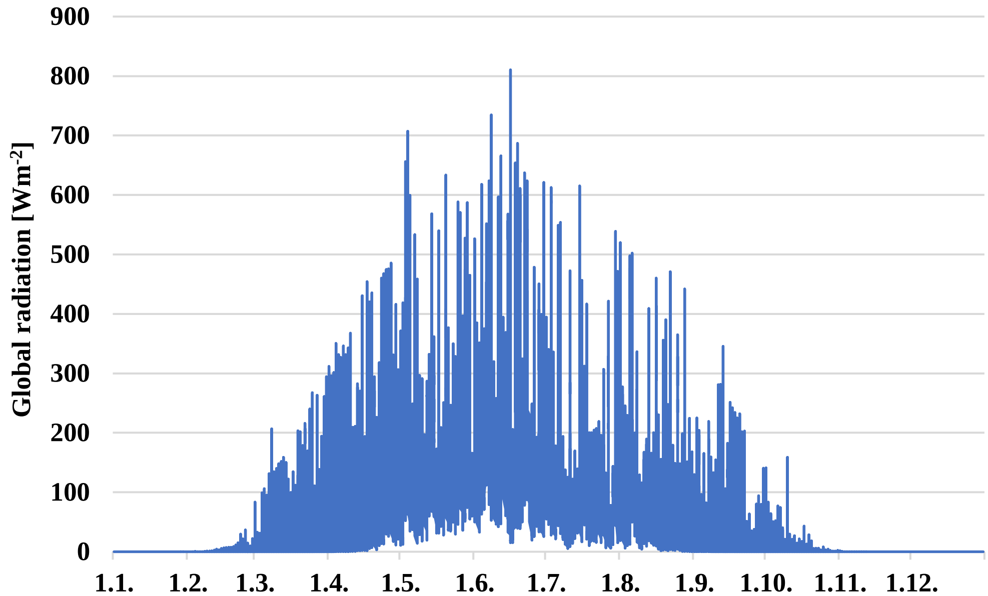

Figure 3. Global radiation on Platåberget in 2018 (Norsk Klimaservicesenter 2020).

In summer, the optimal tilt angle of the solar panels in Svalbard would be 55 ° (Enoksen 2020). Since the global radiation is measured on a horizontal surface, the production distribution is not perfectly correct. The global radiation includes both direct and diffuse radiation. The distribution varying from 0 to 1 is created using the global radiation. The created distribution gives a capacity factor of 9 % calculated by Equation 2. Based on the capacity factor of already existing panels in Longyearbyen, the capacity factor is corrected in EnergyPLAN to be 7 % (Ringkjøb et al. 2020). The solar panels are assumed to be optimally tilted.

The production of the solar PV is calculated hourly by:

$$P = I * A * \eta, \tag{3}$$

where I is the global radiation (Wm^{-2}), A the area of the panels (m^{-2}) and η the efficiency of the panels.

4.3 Electricity and district heat

The energy demand data in Longyearbyen are received from the power plant. The received data consist of hourly district heating and electricity production. The data are recorded from 2017 till 2020 but the year 2018 is used in this study. However, some of the data were missing some single points or the values were obviously unrealistic. In that case, the data point has been replaced with a mean value of previous and following data points, if not stated otherwise. These corrections were made for one period in the electricity data. In the district heating data, the corrections were made for one period and 24 single data points.

The electricity production is received from the Turbines 1 and 2 at the power plant and from the diesel generators at Energiverket and UNIS. The total electricity production is the sum of these. In addition to some single hours missing, between 14th and 20th of July the numbers from Turbine 1 showed 0. The reason could for example be a maintenance break at Mine 7, but since this is uncertain, the values are replaced as the mean of the values in 2017 and 2019. In total, the electricity production was 45.1 GWh in 2018. The electricity production is seen in Fig. 4.

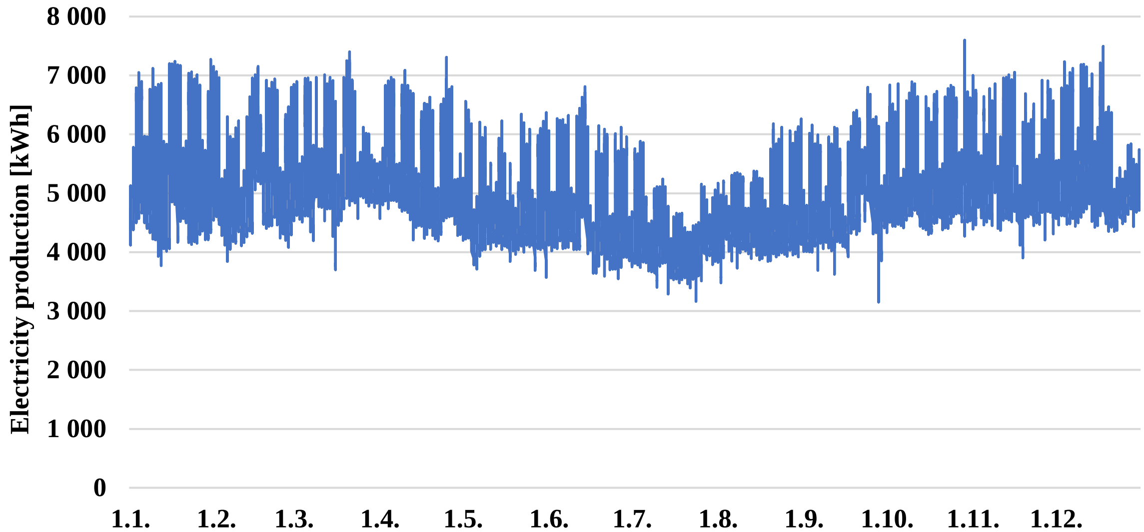

Figure 4. Electricity production data in 2018 after replacing the outliers and gaps.

The district heating data consist of the heat produced at the power plant. Since there is no data of the diesel-fired boilers along the district heat network, they could not be included. The district heating data consisted of several gaps and negative values between 2017 and 2019. The year 2018 was the most consistent. However, there was a period between the 6th and the 31st of December when all the hours showed 2.03 and were not considered realistic. Hence, this period is replaced with the mean values of the 2017 and 2019 values. The other missing or values below 1000 kWh are replaced with the mean of the previous and following hour, in total 24 times. The total district heat production in 2018 was 72.25 GWh in total. The district heat production is seen in Fig. 5.

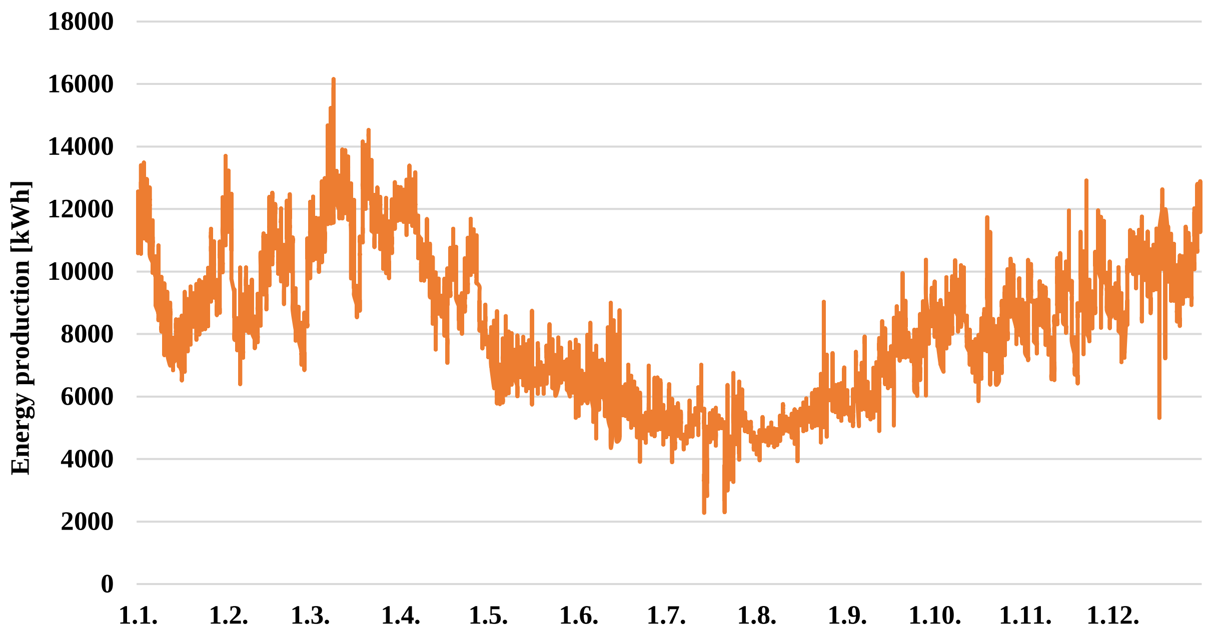

Figure 5. The production of district heating in 2018 after replacing the outliers and gaps.

For this Bachelor's thesis, the demand data for transport fuels was acquired from Circle K Svalbard and LNS Spitsbergen. Despite the attempts, the data were not available and thus the transport sector could not be included in this study.

4.4 EnergyPLAN

In this study, an energy system modelling tool EnergyPLAN is used. EnergyPLAN is a model that simulates the operation of an energy system on an hourly basis. It is especially used to model renewable energy systems. In modelling, the power, heating, cooling, industry, and transport sectors are possible to include. The model is deterministic, which means that with the same initial conditions, the outputs will always be the same instead of an ensemble of different outputs such as in stochastic models. Thus, the uncertainty of the input parameters is not taken into account. However, when modelling several options of the energy system, the different results can be compared and the variability in, for example, wind and solar energy can be considered. The inputs in the model are the energy demand, renewable energy resources, costs of heating of the houses and the district heating, industrial fuel demand and the fuel demand for transportation. As outputs, the model gives the shares of different energy sources, fuel consumption, the amount of import or export of electricity, CO_2 emissions and total costs. EnergyPLAN uses a leap year and thus it requires 8784 data points. Since the data are from 2018, the extra 24 hours are added in the data set by copying the last day of the year. (EnergyPLAN 2020.)

4.5 Costs

The costs used in this thesis are mostly retrieved from the cost database of EnergyPLAN (EnergyPLAN 2020). Some costs are retrieved from different sources to obtain more updated values for the modelling. The costs of the reference year 2018 are actually the costs projected for 2020. However, this should not have a significant impact. The costs of the future scenario are the costs for 2030. An interest rate of 7 % is used in all the cases. The fuel price of 2.8 €/GJ for coal is used. The numbers of all the costs used in the modelling, the investment periods, and the sources of some updated values are seen in the Appendices 1 and 2.

4.6 Scenarios

The first scenario simulates the current system with coal and diesel as the energy sources. The year 2018 is used as a reference year. The existing solar PV is not taken into consideration since the share of it is so low. The reference scenario is created for comparing the installed capacities and the costs of the system to the other future scenarios. The losses of the district heating system are not known but are assumed to be 15 %. To get a correct heat demand that is known to be around 72.25 GWh, the heat production is set to be 85 GWh with the assumed losses of 15 %. It is higher than the actual production at the power plant. Since there were no data of the diesel boilers along the district heat network, the number 85 GWh also represents them.

In the first future scenario, the energy system for the year 2030 is created. The same electricity and heat demand distributions are used except the electricity demands of the coal-fired power plant and Mine 7 are subtracted. It is assumed that before 2030 the coal mining has stopped, and the current power plant is replaced. Thus, the future electricity demand is assumed to be 70 % of the current demand. It is assumed that the population stays at the same level and significant improvements in the energy efficiency of the buildings are not made. Hence, the heat demand is assumed to stay at the same level. The second future scenario for the 2030 is modelled with lower demands. The annual electricity demand is set to 25 GWh and the heat demand to 52 GWh based on Rinkjøb et al. (2020) assumptions. The population is assumed to stay at the current level. The energy efficiency of the buildings is assumed to improve, and the new and renovated buildings replace the current ones at the rate of 2.3 % and the energy efficiency in the service sector increases by 1 % per year. The electricity demands of the coal-fired power plant and Mine 7 are also reduced. (Rinkjøb et al. 2020.) The demand assumptions are seen in Fig. 6.

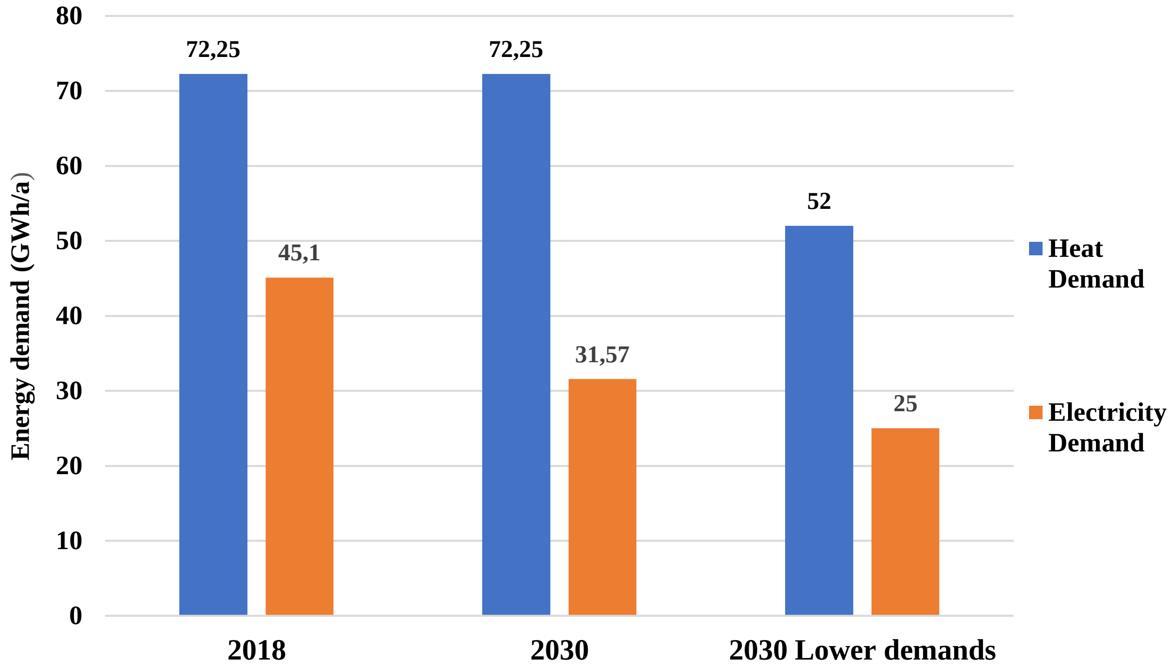

Figure 6. The heat and electricity demand assumptions in the scenarios *2018*, *2030* and *2030 Lower demands*.

The flow charts of the current and the future renewable systems are seen in Figs. 7 and 8. In the current system coal and diesel are used as the energy sources. The CHP power plant produces the electricity and heat. Diesel is also used in the boilers ("Fyrhusene"), along the district heat network. Since there is no data of the diesel boilers and the amount of diesel used in the CHP power plant is low, only coal is used in the modelling.

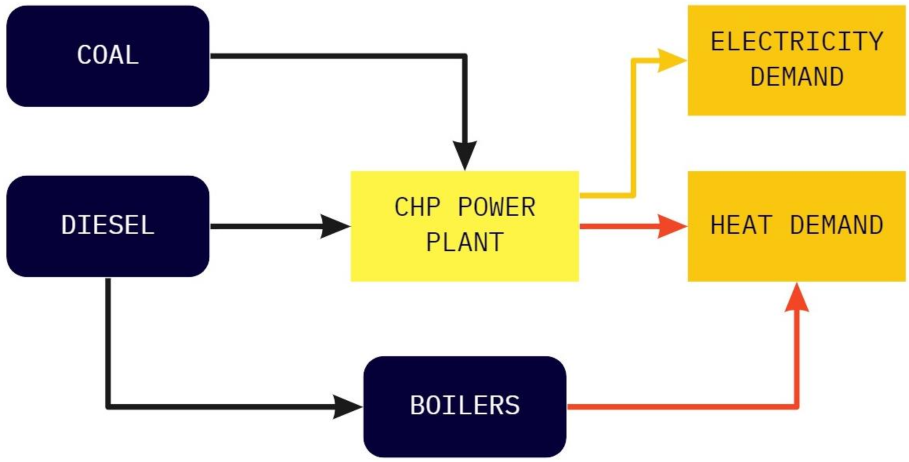

Figure 7. The reference scenario representing the current energy system. The diesel boilers along the district heat network are not included in modelling since there were no data of them.

In the renewable scenarios, onshore and offshore wind and solar PV produce electricity. This electricity is used straight in the electricity demand and in the Power-to-Gas process. The electrolysers split water into hydrogen and oxygen. CO_2 is captured from the air in a process called direct air capture. The hydrogen and captured CO_2 are combined to create methane CH_4. The created synthetic methane is used as the fuel in the new CHP power plant, which produces heat and electricity. The methane can also be stored and used later when the demand is higher. Liquefying the methane has not been included in the system. Batteries also store electricity and are used in the peak electricity demand times. Furthermore, a centralised electric heat pump contributes to the heat demand with a thermal storage.

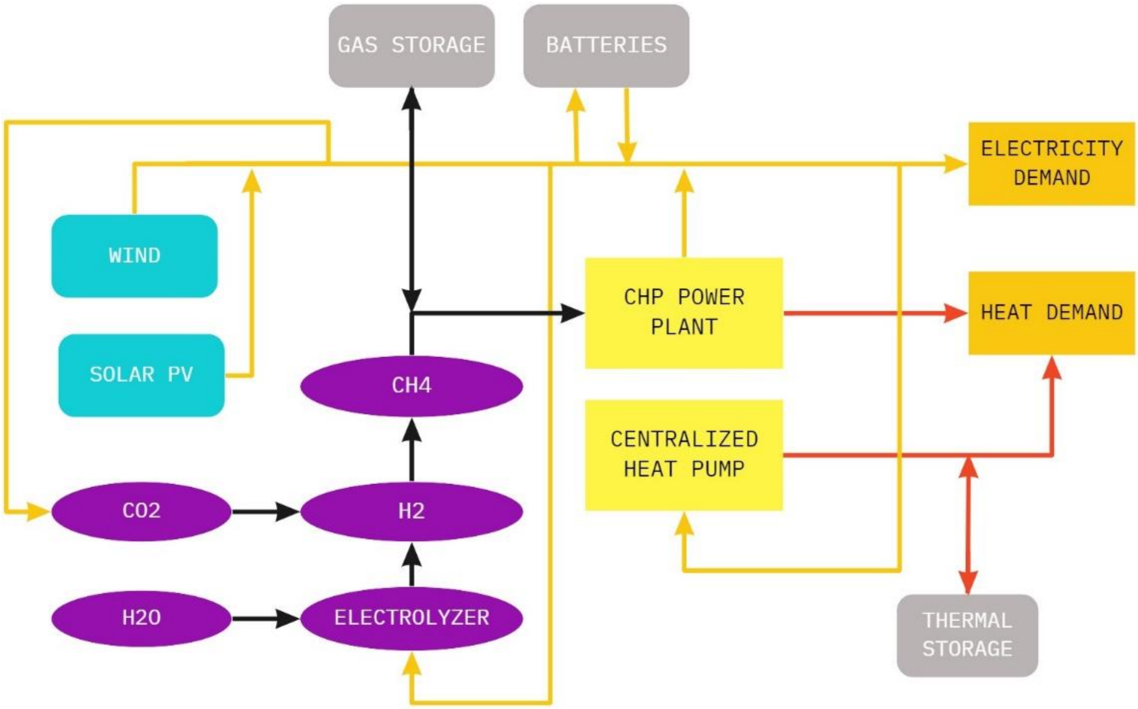

Figure 8. A possible scenario for the future 100 % renewable energy system.

5 RESULTS

In this section, the key results of the different scenarios modelled with EnergyPLAN are presented. The main focus is to create a 100 % renewable energy system in the most cost-effective way. In this regard, the EnergyPLAN model is not an optimisation model, but the user can adjust inputs to see the influence on costs, thereby creating more cost-effective solutions. The system is modelled as an independent island system without imported energy to get an overview of the capacities needed.

The annual primary energy used in the different systems for electricity generation is shown in Fig 9. In the reference scenario, only coal is used to produce the electricity and heat needed with 207 GWh. Thus, in the modelled results, the diesel that is used in the backup generators and the district heat boilers, is not taken into account. In the *2030* scenario, 16.95 GWh of onshore wind, 65.9 GWh of offshore wind and 1.95 GWh of solar PV form the primary energy. In the *2030 Lower demands* scenario, 25.4 GWh of onshore wind, 32.9 GWh of offshore wind, and 4.82 GWh of solar PV are the primary energies.

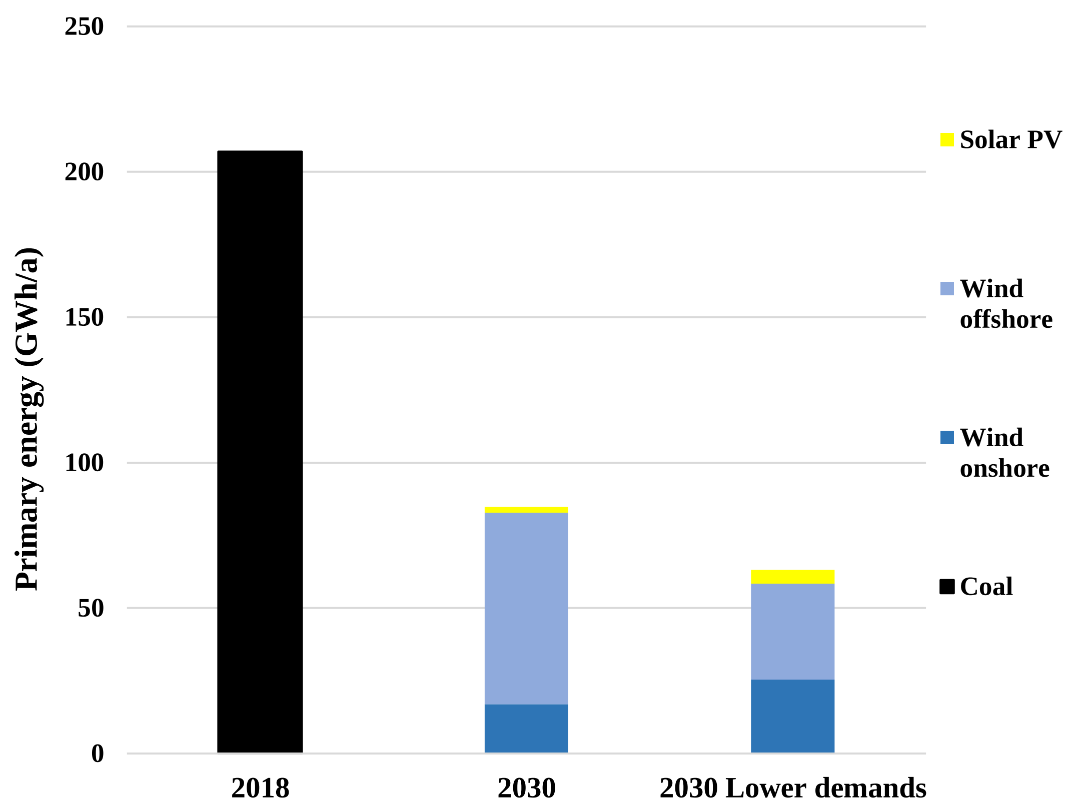

Figure 9. The primary energy used in the electricity generation in the scenarios *2018*, *2030* and *2030 Lower demands*.

The installed electricity generation capacities in MW_e are seen in Fig. 10. In the *2018* scenario, the capacity of the CHP is 7.5 MW, and the capacity of the condensing turbine is 8.9 MW. In the *2030* scenario, the capacities of the CHP, solar PV, offshore wind, and onshore wind are 6 MW, 3.03 MW, 16 MW and 6.9 MW, respectively. In the *2030 Lower demands* scenario the capacities of the CHP, solar PV, offshore wind, and onshore wind are 5 MW, 7.49 MW, 8 MW and 10.35 MW, respectively. The capacity of the methanation process in the *2030* scenario is 9.17 MW_{gas} and in the *2030 Lower demands* scenario 8.02 MW_{gas}.

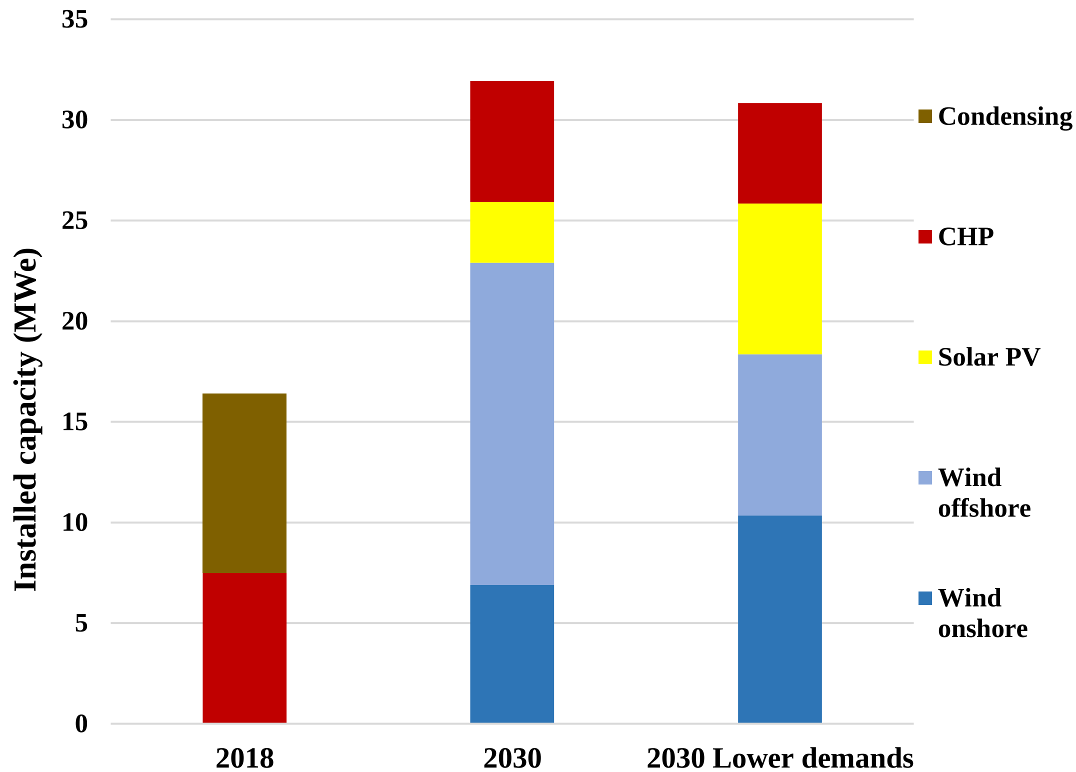

Figure 10. Installed generation capacities in the scenarios *2018*, *2030* and *2030 Lower demands*.

The electricity consumptions in the three scenarios are seen in Fig 11. The electricity consumption in the *2018* scenario consists of the consumption of the households and industry being 45.1 GWh. In the future scenarios, the electricity consumption is remarkably higher. In the *2030* scenario, the electricity consumption is 95 GWh, the electrolysers consuming the largest part with 44.5 GWh. The households and industry consume 31.6 GWh based on the assumptions described in Section 4.6. The heat pumps (or a centralized heat pump) consume 17.2 GWh and the carbon capture 1.13 GWh. There is also excess electricity, or curtailment, of 0.59 GWh. In the *2030 Lower demands* scenario, the electricity consumption is 70.6 GWh. Similarly, electrolysers are the largest consumer with 32.2 GWh. The households and industry consume 25 GWh (see assumptions in Section 4.6). The heat pumps consume 12.3 GWh, carbon capture 0.82 GWh, and the excess electricity or curtailment is 0.18 GWh.

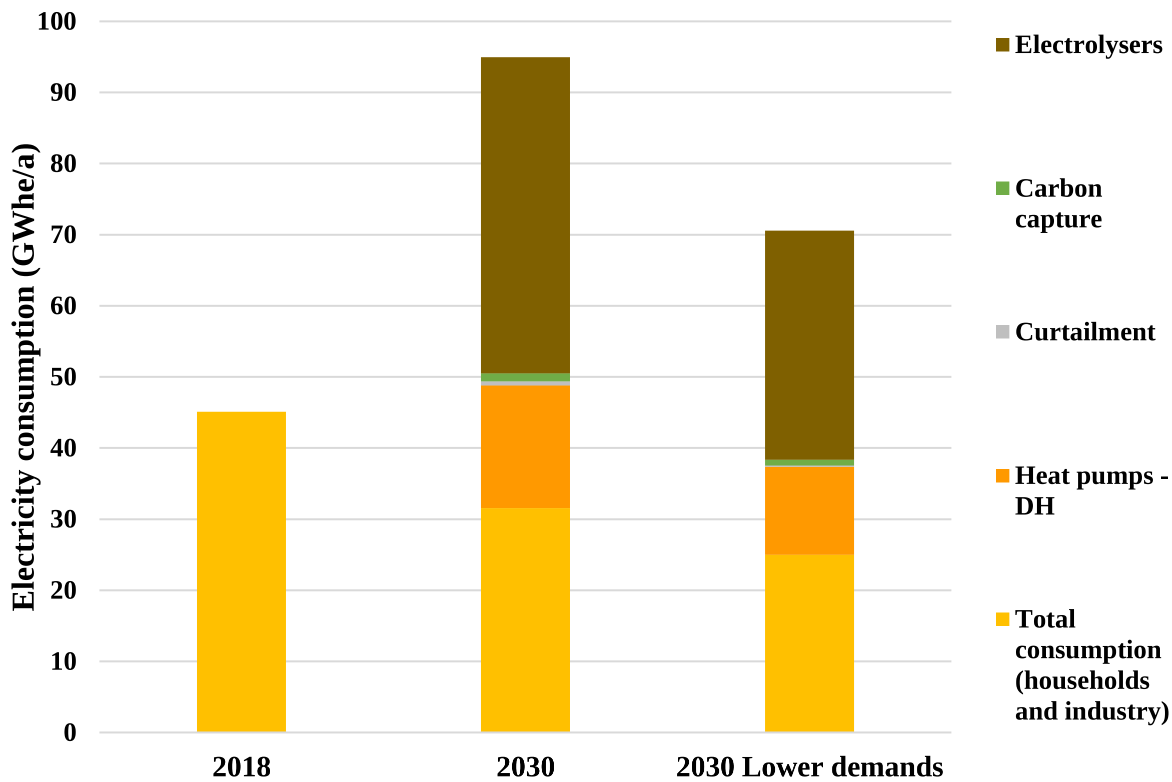

Figure 11. Electricity consumption in the scenarios *2018, 2030* and *2030 Lower demands*.

The electricity productions in the three scenarios are seen in Fig. 12. Electricity in the *2018* scenario is produced at the coal-fired power plant. The CHP, referring to the Turbine 1, which produces both heat and electricity, produces 25.63 GWh of the electricity. The condensing mode, Turbine 2, produces 19.5 GWh of the electricity. In the *2030* scenario, the electricity is mainly produced with wind power and solar PV. The offshore wind produces 65.9 GWh, the onshore wind 17 GWh and the solar PV 1.95 GWh. The CHP power plant that uses synthetic methane as a fuel, produces 10.2 GWh of electricity. In the *2030 Lower demands* scenario, offshore wind, onshore wind, and solar PV produce 32.9 GWh, 25.4 GWh, and 4.8 GWh, respectively. The CHP power plant produces 7.4 GWh of electricity.

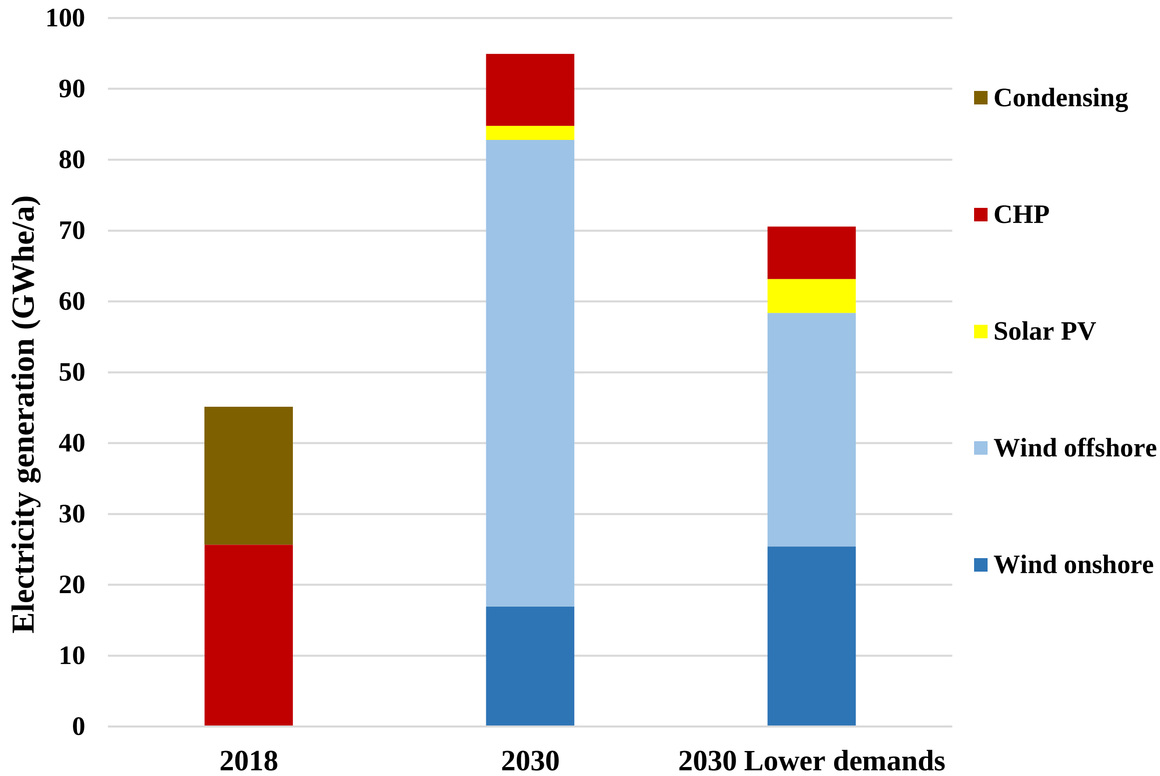

Figure 12. The electricity productions in the scenarios *2018*, 2030 and *2030 Lower demands.*

The total annual costs of the systems in the three scenarios are seen in Fig 13. The *2018* scenario is the cheapest and the *2030* scenario the most expensive. The costs of the *2018* scenario are 5.65 M€ per year. The highest costs are caused by 2.7 M€ of annualised investment costs and 2.1 M€ of fuels costs. The fixed operation costs are 0.67 M€ and other variable costs 0.13 M€. The costs of the CO_2 emissions are calculated as well but since Svalbard is not part of the EU Emissions Trading System (EU ETS), they are not included in the results. The total annual costs of the *2030* scenario are 8.74 M€. A major part of the costs are investment costs with the value of 6.9 M€. The fixed operation costs are 1.8 M€, other variable costs 0.037 M€ and fuel costs 0.019 M€. The *2030 Lower demands* scenario has total annual costs of 6.97 M€. The annualised investment costs are 5.4 M€, fixed operation costs 1.5 M€, variable costs 0.027 M€, and fuel costs 0.014 M€.

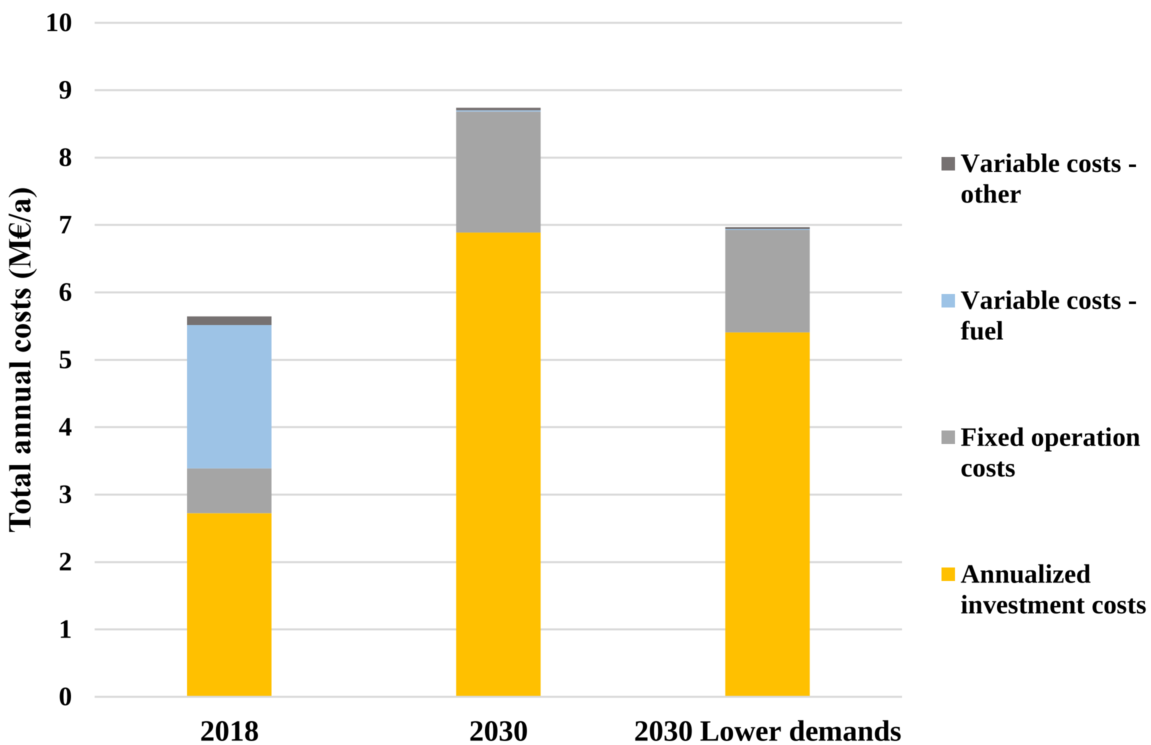

Figure 13. The total annual costs of the systems in the scenarios *2018*, *2030* and *2030 Lower demands*.

6 DISCUSSION

In this section, the results of the installed capacities are compared to the previous studies. The effect of the uncertainties in the data and the assumptions are investigated and the importance of the transport sector is discussed. The costs of the different scenarios are compared. Also, the environmental impacts of the installations are considered.

6.1 Installed capacities

In the *2030* scenario, the offshore wind capacity corresponds to two offshore wind turbines and onshore capacity to two onshore wind turbines. The system in the *2030 Lower demands* scenario requires one offshore wind turbine and three onshore wind turbines. Therefore, both scenarios only need four turbines. The area of the needed solar panels can be calculated by Equation 3. The annual total irradiation is 626 kWh m^{-2} based on the radiation data from Platåberget in 2018 and the efficiency of the panels are assumed to be 16.9 % based on the already installed panels at Svalbard Airport (Enoksen 2020). In the *2030* scenario the production is 1.95 GWh, which gives an area of 18 400 m^2. In the *2030 Lower demands* scenario the needed area with the production of 4.8 GWh is 45 300 m^2 of solar panels. The areas are reasonable for a solar park on Platåberget. The area could be decreased by including rooftop panels as well.

The required installed capacities are remarkably lower than in the previous studies. In the *"Isolated system"* -scenario in Ringkjøb et al. (2020), the installed onshore wind capacity is 126 MW and the solar PV capacity 119 MW. In the "*HYD"* scenario with imported hydrogen, the capacities are 18 MW of onshore wind and 6 MW of solar PV. (Ringkjøb et al. 2020.) In the 80 % renewable scenario in Tennbakk et al. (2018), the onshore wind capacity is 63 MW and the solar PV 25 MW. However, the energy systems in the previous studies are different and neither are based on producing methane from hydrogen and CO_2. In addition to this, the other studies did not include offshore wind. The offshore wind has the highest annual capacity factor and thus lowers other needed installed capacities.

6.2 Uncertainties in the input data and assumptions

The wind power forms a large part of the modelled future energy systems. The wind speeds at the hub height were calculated using a logarithmic wind profile, as described in the Section 4, and the atmosphere is then assumed to be neutral. However, in Svalbard, the atmosphere is usually stable and thus the wind speeds at the hub height may differ from those calculated. Stable atmosphere is common during winter due to the surface cooling. Near the surface, wind speed increases more rapidly in the neutral atmosphere than in the stable atmosphere. Higher up, wind speeds are higher in the stable atmosphere. (Wallace & Hobbs 2006.) Also, the chosen roughness length, which represents the roughness of the surface, affects the wind speeds. The larger the roughness length is, the higher the wind speeds are at the hub height. In this bachelor's thesis, the wind speeds were calculated with the roughness length of 0.002 m. In a study made about a valley Adventdalen, the roughness length varies from 0.0002 – 0.002 m depending on the snow cover (Frank 2020). Also, the local topography largely affects the wind conditions. Thus, the actual wind production rates and capacities may vary from the results modelled. In addition to the uncertainties in the wind speeds, the effect of the icing must be considered, especially when installing the turbines at higher elevation. To estimate the needed capacities, more investigation of the wind power in Svalbard and the Arctic is needed.

The solar power production in this Bachelor's thesis is based on the global radiation measured on a horizontal surface. To obtain more accurate production data, the radiation into a tilted surface should be used. Since the angle of the panels affect the solar PV production, there are uncertainties in the modelled productions. Also, the choice of different panel types affects the production. For example, two-faced panels increase the production in winter, when the reflection from the snow cover can be utilized better. Additionally, the solar panel efficiencies have increased considerably during the last decades. The trend is continuing and thus the efficiencies will be higher in 2030 than in the current panels at the airport, which increases the production (IRENA 2019).

The other uncertainties are related to for example the future energy demand. The population was assumed to stay at the current level for 2030 scenarios. Also, the *2030 Lower demands* scenario is based on the large improvements in the energy efficiency. If the improvements do not take place, it affects the needed installed capacities. In the future, the heat demand may decrease due to the rising temperatures. On the contrary, a warmer climate may require cooling of the buildings in summer, which has not been included in the modelling.

6.3 Transport sector

To obtain more complete and realistic view of the renewable system, the transportation sector is essential to include to the modelling. Longyearbyen's transportation sector is unique since snowmobiles form a large part of the transport sector. In 2018, there were 2136 snowmobiles, 1114 private cars, 62 combined vehicles and 26 buses (Statistics Norway 2020). Also, cruise ships and boats are significant parts of the transport sector. In the future, the produced hydrogen could be used in the fuels for the vehicles. Also, electrifying transport affect the installed capacities needed. Electrifying snowmobiles could mean that their batteries could be used, for example, for the solar panels in summertime. The distances the cars are driven in Longyearbyen are relatively short due to the limited road infrastructure. Thus, electrifying the transport sector or for example car sharing would be feasible.

Electrifying the transport sector would also make the system more flexible for example via vehicle-to-grid (V2G). In V2G, the electricity can be returned to the power grid from the batteries of electric vehicles when needed. Consequently, it allows higher shares of renewable energy and efficiency of power grids can be increased. In an economic perspective, V2G can offer benefits by making power grids more cost-effective and profiting vehicle owners. Child et al. (2018) show in a study made for Åland that high participation in V2G reduces installed capacities and total annualized costs. The capacities of gas storage, electrolyser, methanation and offshore wind power were lower in the scenario with high V2G participation compared to low V2G participation. (Child et al. 2018.) An electrified transport sector would provide a wide range of opportunities to improve the renewable system and thus is important to be investigated.

6.4 Comparison of the costs

The *2030* scenario has the highest costs of the three scenarios, and the *2030 Lower demands* has the second highest costs. However, although the annual costs of the renewable systems are higher, the nature of the costs is different. In the future scenarios, investment and maintenance costs are the highest. In the *2018* scenario, in addition to investment and maintenance costs, fuel costs form a major part of the total costs. In a study about a 100 % global renewable energy system, Ram et al. (2019) show that a transition into a renewable energy system provides local jobs in the power sector. The higher investment and maintenance costs stand for local jobs. The fuel costs form a large part of the costs in the current system, which – when the coal mining ends – does not benefit the local economy. Thus, even though the costs of the future systems are higher, it can provide jobs and is a benefit for the community. All the scenarios are modelled with an interest rate of 7 %, and thus the costs present a more conservative results compared to lower interest rates. For example, Ringkjøb et al. (2020) used an interest rate of 4 %.

The *2018* scenario would be considerably more expensive if the cost of CO_2 emissions would be counted. The emissions in 2018 are calculated to be 73 400 tons. With a price of 28€ per

tCO_2, that would lead to 2.1 M€ annual costs (Ember 2020). Thus, the total annual costs would be 7.7 M€, so 1.04 M€ lower than the *2030* scenario and 0.73 M€ more expensive than the *2030 Lower demands* scenario. It is not known that Svalbard would be planned to be taken part of EU ETS. However, if that happened, significantly higher costs would also pressure the transition into low emission solutions.

6.5 Environmental impacts

A renewable system would reduce the CO_2 emissions by around 73 400 tons annually. Consequently, the emissions of nitrogen and sulphur oxides and particles would also be reduced. However, the modelled renewable system would require significant installations: wind turbines, solar panels, a new power plant, a centralised heat pump, thermal storage, facilities for the Power-to-Gas process and the gas storage. These installations have environmental impacts and especially the impacts on the sensitive Arctic environment needs to be considered. However, some installations would nonetheless have to be done. For example, the current aging power plant is already planned to be moved to Hotellneset (Tennbakk et al. 2018). The major concern is the effects of the wind turbines on the environment and the landscape. According to the evaluation of Tennbakk et al. (2018) the possible disadvantages of the wind turbines are, for example, collisions with birds, the loss of habitats or the effects on nesting. However, in both the scenarios, only four wind turbines would be needed. Tennbakk et al. (2018) have not included offshore wind in due to higher costs and possible environmental impacts. According to Piasecka et al. (2019), onshore wind power plants have higher environmental impacts compared to offshore wind power plants. With higher capacity factors, offshore wind turbines could decrease the number of turbines needed, and thus reduce the environmental and also visual harms.

7 CONCLUSION

The results of the modelled scenarios show that a 100 % renewable system for Longyearbyen in 2030 is achievable. The renewable system uses onshore and offshore wind, and solar PV as the primary energy. Wind power, especially the offshore wind, plays an important role in the renewable scenarios. The new power plant would be run on synthetic methane that is produces from the hydrogen and CO_2. The modelled capacities are lower compared to the earlier studies made. However, this is the first simulation of an energy system for Longyearbyen that uses synthetic methane and in the previous studies, offshore wind was not included. The total annual costs of the future scenarios are higher than in the *2018* scenario, but the renewable systems save gradually in fuel costs and also CO_2 emission costs if they were included. Investment and maintenance costs also stand for local jobs and thus can benefit the local economy. To conclude, a renewable energy system for Longyearbyen is seen feasible but several factors, such as the transport sector and environmental impacts, must be investigated to get a more precise view of the future system.

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Costs assumptions 2018 (EnergyPLAN 2020).

Production type	Investment costs [kEUR/unit]	Period [a]	Operation and maintenance [%]
Heat storage CHP	3	20	0.7
Boilers	0.075	35	3.7
Large CHP units	1.63	40	1.63
Large power plants	0.385	30	2.99
District heating substations [1]	6200	20	2.42
District heating network	72	40	1.25

[1] The costs were calculated for 1006 buildings. (Tennbakk et al. 2018.)

Costs assumptions 2030 (EnergyPLAN 2020).

Production type	Investment costs [kEUR/unit]	Period [a]	Operation and Maintenance [%]
Large CHP units	0.83	25	3.35
Heat Storage CHP	3	20	0.7
Heat pumps	2.83	25	0.34
El 1 storage cap [1]	142	20	2.8
Onshore wind	0.91	30	3.27
Offshore wind	1.75	30	1.94
Photo Voltaic	0.85	40	1
Carbon recycling [2]	338	25	4
Methanation [3]	0.309	30	4.6
Electrolyser [1]	0.312	30	3.5
Hydrogen storage	7.6	25	2.5
Gas storage	0.05	50	2.6
District heating substations	6200	20	2.42
District heating network	72	40	1.25

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