Tampereen yliopisto

Topias Tuomola

IMPROVING THE USE OF RENEWABLE ENERGY IN NYKARLEBY

Faculty of Information Technology
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ABSTRACT

Topias Tuomola: Improving the use of renewable energy in Nykarleby
Master's Thesis
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Keywords: renewable energy, solar power, energy storage, Nykarleby

This master's thesis is concentrating on the state of renewable energy production in Nykarleby and what kind of plans have already been made to increase the share of renewable energy production in the future. There are hydro power, wind power and biogas power plants already in the city and the number of wind power plants will increase in the next few years.The amount of wind power would increase from 7 MW to 370 MW.

In addition to reviewing the current plans, the thesis gives an estimation of how much energy can be produced with solar power in Nykarleby. The amount of produced energy stays close to that of the most southern city of Finland, Hanko, when the power of the plant is taken into consideration. For the solar power plant there are two different business models. In the first one, there is one company which builds the plant and then sells it to the investor, who takes care of it for its 30 years of operation time. This is not profitable for the builder, because of the low estimation of the selling price. However, for the investor it would be good business, since the payback time for the investor is under 19 years. In the second model, one company takes care of the plant all the way from the building phase to the 30 years of operation time and gets the income from selling the electricity. With this model the payback time is under 22 years, so it is feasible for the company.

The latter part of the thesis concentrates on how the energy storage system could be used alongside a wind power plant. Profitability calculations have been made for Björkbacken wind power plant, which is planned to be built in Nykarleby. Financial point of view concentrates on the first 10 years of operation, during which there usually is a contract, stating that the plant must produce a specific amount of energy every hour. The deficit must be compensated by energy purchases from the market. Then there is another company, which buys the amount of energy stated in the contract at fixed price. The need to buy energy is reduced from 37 % of annual hours to 24-36 % when the energy storage is taken into use. The reduction depends on the capacity of the storage and how much energy must be produced according to the contract. Today the price for the contract could be 3.1 c/kWh and with that price the savings from the decreased amount of electricity that must be bought will not cover the investment costs of the storage. For profitable investment the price of the contract should be at least 3.3 c/kWh.

In addition to the energy storage setup described above, another option could be a power-to-gas system, which could produce hydrogen out of water. Hydrogen could be used in the biogas plant, which is located right next to the wind farm, and they could use the hydrogen with carbon dioxide to produce methane. If 20 % of the energy produced by the wind farm would be used for hydrogen production, it would cover 95 % of the maximum hydrogen need of the biogas plant. Surplus hydrogen could be used as fuel for passenger cars, he popularity of which will depend on the number of hydrogen refuelling stations in Finland.

The originality of this thesis has been checked using the Turnitin Originality Check service.

TIIVISTELMÄ

Topias Tuomola: Uusiutuvan energian käytön tehostaminen Uudessakaarlepyyssä
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Tämä diplomityö käsittelee uusiutuvan energian käyttöä Uudessakaarlepyyssä, ja mitä suunnitelmia sen kehittämiseksi on jo tiedossa. Kaupungissa on jo uusiutuvan energian tuotantoa vesi- ja tuulivoiman sekä biokaasun muodossa. Seuraavien viiden vuoden aikana tuulivoiman osuus uusiutuvan energian tuotannosta tulee todennäköisesti moninkertaistumaan, sillä nykyinen 7 MW:n teho voi parhaimmillaan kasvaa jopa 370 MW:iin.

Valmiiden suunnitelmien lisäksi työssä on selvitetty aurinkovoimalan potentiaalia Uudenkaarlepyyn alueella sekä tuotetun energian että talouden näkökulmasta. Tuotetun energian osalta voidaan pohjoisemmasta sijainnista huolimatta päästä lähelle Hangon lukemia, kun tuotettu energia suhteutetaan voimalan tehoon. Taloudellisesta näkökulmasta on keskitytty kahteen erilaiseen investointimalliin. Ensimmäisessä yksi yritys suunnittelee ja valmistaa voimalan, minkä jälkeen se myydään investoijalle, joka hallinnoi sitä sen elinkaaren ajan. Tämä malli ei ole kannattavaa voimalaa rakentavalle yritykselle, sillä myyntihinta jää arvion mukaan turhan alhaiseksi. Mutta toisaalta malli olisi kannattava voimalaan investoivalle yritykselle, joka saisi investointikustannuksensa takaisin alle 19 vuodessa. Toisessa mallissa yksi yritys vastaisi voimalasta rakentamisen lisäksi koko elinkaaren ajan ja saisi tulonsa sähkönmyynnistä markkinoille. Tässä tapauksessa investointi olisi kannattavaa yritykselle ja sen olisi mahdollista saada sijoituksensa takaisin alle 22 vuodessa aurinkovoimalan elinkaaren ollessa molemmissa tapauksissa 30 vuotta.

Työn toisessa pääkokonaisuudessa on käsitelty energian varastointia ja sen kannattavuutta tuulivoimalan yhteydessä. Tuulivoimalaesimerkkinä on käytetty kaupungin alueelle suunnitteilla olevaa Björkbackenin tuulivoimalaa. Taloudellinen näkökulma keskittyy voimalan toiminnan ensimmäisiin 10 vuoteen. Tällöin tuulivoimaloissa on yleensä voimassa sopimus, jonka perusteella sen täytyy tuottaa sovittu määrä energiaa tai hankkia se markkinoilta, jos tuotanto itsessään ei riitä. Sopimuksen toinen osapuoli lupautuu ostamaan sovitun energiamäärän kiinteällä hinnalla. Akkuvarastoinnin avulla tarve ostaa sähköä markkinoilta laskee 24–36 %:n välille alkuperäisestä 37 %:sta, kun tarkastellaan sellaisten tuntien osuutta vuodessa, jolloin sähköä täytyy ostaa markkinoilta. Tulos riippuu varaston kapasiteetista ja halutusta tasosta energian myynnin sopimuksessa. Tämä parannus ei kuitenkaan kata energian varastoinnista koituvia kuluja, vaan parhaimmassakin tapauksessa sopimuksen mukaisen energian myynnin hinnan täytyisi nousta 3,1 snt/kWh:sta 3,3 snt/kWh:iin, jotta varastointi olisi kannattavaa.

Akkuvarastoinin lisäksi mahdollinen ratkaisu voisi olla power-to-gas -järjestelmä, jolla voitaisiin tuottaa vetyä elektrolyysin avulla vedestä. Tuotettu vety voitaisiin hyödyntää ensisijaisesti tuulivoimalan vieressä toimivassa biokaasulaitoksessa, joka voisi hyödyntää sitä yhdessä hiilidioksidin kanssa metaanin valmistuksessa. Jos 20 % tuulivoimalan arvioidusta tuotannosta käytettäisiin vedyn valmistukseen, sillä voitaisiin kattaa parhaimmillaan 95 % biokaasulaitoksen vedyn maksimitarpeesta. Tämän jälkeen ylijäänyttä osaa vedystä voitaisiin hyödyntää henkilöautojen polttoaineena. Tätä toimintaa rajoittaa se, kuinka paljon vedyn tankkausasemia tullaan Suomessa tulevaisuudessa rakentamaan.

PREFACE

This thesis is made for Energiequelle Oy and the idea for the thesis was to investigate what is the current situation of renewable energy in Nykarleby and how the use of them could be improved in the future. It has been great to be part of the work community and I would like to thank everyone in Energiequelle Oy and Energiequelle GmbH, who has helped me during the work. Special mention for Nils Borstelmann, who has been a big help for the whole time from defining the topic to pointing to the right direction during the writing.

I would like to thank the primary examiner, Lecturer Risto Mikkonen from Tampere University, who helped to create the structure for the thesis and gave feedback during the writing of the thesis. I would also like to thank another examiner, Professor Seppo Valkealahti from Tampere University, for feedback during the writing of the thesis.

Finally, I would like to thank my family and friends who have been big support for the studies and the thesis.

Tampere, 4.2.2021

Topias Tuomola

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AFC	Alkaline Fuel Cell
AM	Air Mass
CAES	Compressed Air Energy Storage
CdTe	Cadmium telluride
CHP	Combined Heat and Power
CIGS	Copper indium gallium selenide
DOD	Depth of Discharge
FF	Fill factor
I_{SC}	Short-circuit current
MCFC	Molten Carbonate Fuel Cell
MPP	Maximum power point
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PHS	Pumped Hydro Storage
PPA	Power Purchase Agreement
PtG	Power to Gas
SMES	Superconducting Magnetic Energy Storage
SNG	Synthetic Natural Gas
SOC	State of Charge
SOE	Solid Oxide Electrolysis
SOFC	Solid Oxide Fuel Cell
SOH	State of Health
V_{OC}	Open-circuit voltage
α_s	Solar altitude angle
γ_s	Solar azimuth angle
θ_z	Solar zenith angle

1. INTRODUCTION

Role of renewable energy in energy production has been increasing significantly in recent years. This development will continue in the future all over the world but also in Finland, which is important in a fight against climate change. In Finland hydro power has had the largest share of energy production out of renewable energy technologies. For hydro power there is a limited number of locations where it can be used. For wind power there are more useful locations, and it is now the fastest growing part of the renewable energy production in Finland and also in Nykarleby. To increase the share of renewable energy in the energy production, it is necessary to use all the available renewable technologies and to find out what is the most effective way to use them.

Nykarleby is a small city on the west coast of Finland and it already has some renewable energy production. This thesis has a goal to give clear a picture what is the status of renewable energy production in the city and what kind of plans have been already made for the next few years to increase the renewable energy production. After those plans it is important to think what the next steps could be. Wind power and biogas production have already shown their potential in the area, so it is reasonable to concentrate on other technologies instead. One option is solar power, and it is important to find out what kind of energy potential it would have in Nykarleby. Alongside energy potential it is essential to consider the financial side of a large-scale solar power plant and how feasible investment it would be.

When concentrating on renewable energy it is also important to get the most out of the power plants that produce energy. Many of the renewable energies are dependent on the weather and the production is not usually consistent. This is the case with wind power and the use of the wind power could be improved by energy storage systems. The production can be levelled with energy storage systems, but it is interesting to know if the storage is a good investment. Is it better to build a wind power plant with energy storage or without it? Battery systems would probably be the obvious choice for energy storage right now, but the situation might change in the future. One option in the future is power-to-gas -systems and how the produced hydrogen could be used in an effective way.

Thesis starts with explanation how the topic of the thesis has taken its shape and why Nykarleby was chosen for the location for this report. This is followed by a status update of the renewable energy production in Nykarleby and what kind of plans are already made for the next few years. Before the estimation for solar power potential there is a theory part for solar power, which goes through the radiation and operation of the photovoltaic cell. Then the financial side of the solar power plant is explained and with two different kinds of business models. This is followed by the theory part for storage systems concentration being battery storage and power to gas -systems. This leads to the final part, which is the use of energy storage alongside a wind farm.

2. BACKGROUND

Energy production is shifting more and more towards renewable energy and distributed generation. But why is it interesting to improve the use of renewable energy in Nykarleby? Nykarleby is a city located in Ostrobothnia at the mouth of Lapua river on the west coast of Finland. There are about 7 500 inhabitants in the city. City is bilingual with 89 % of the population speaking Swedish and 9 % Finnish.

There is already some renewable energy production in the city and there are plans to increase the amount of production from renewable energy in the next few years. There are four different wind farms in a planning or in construction phase and there is also a desire in the municipality to make Nykarleby a more friendly city for the climate. Sören Lawast, a member of the council in Nykarleby, has filed a motion (04.02.2019) that the city should investigate how much existing renewable energy sources improve the climate in the immediate city area and use this information to create an image for Nykarleby as a climate smart city in Finland.

This master’s thesis has been made in cooperation with Energiequelle Oy and because of their request the thesis has been written in English, which also fits well in the bilingual nature of Nykarleby. But how does Energiequelle fit into all this? Energiequelle is one of the companies planning to build wind farm in Nykarleby and in Björkbacken to be more specific. In Finland Energiequelle has been concentrating on wind power but in Europe Energiequelle GmbH has been part of developing all kinds of renewable energy solutions for over 20 years. Energiequelle is interested in being a companion for Nykarleby on its way to become a more climate friendly city beyond the planned wind power plant. Idea for this thesis started from Energiequelle’s Feldheim-project where they built an energy self-sufficient village in Feldheim, Germany. Point of view for the thesis changed a little bit from planning similar a village in Nykarleby to be something more useful for the whole municipality. Idea for the thesis would be to find out what is the current situation with renewable energy production in the city and what kind of solutions could be the next steps towards making the city more climate friendly. Wind power is one feasible solution in Nykarleby, which can be seen from the several ongoing wind farm projects. Goal for the thesis is to consider other types of renewable energy to support wind power.

3. RENEWABLE ENERGY IN NYKARLEBY

To improve the use of renewable energy in Nykarleby, there is a need to find out what is the current situation with renewable energy. This chapter explains the current situation with renewable energy production, which are already in place and introduces what has been planned for the next few years.

3.1 Current situation

There is already some renewable energy production in Nykarleby. Locations for these power plants are shown in figure 1. This section introduces those power plants that are already producing energy.

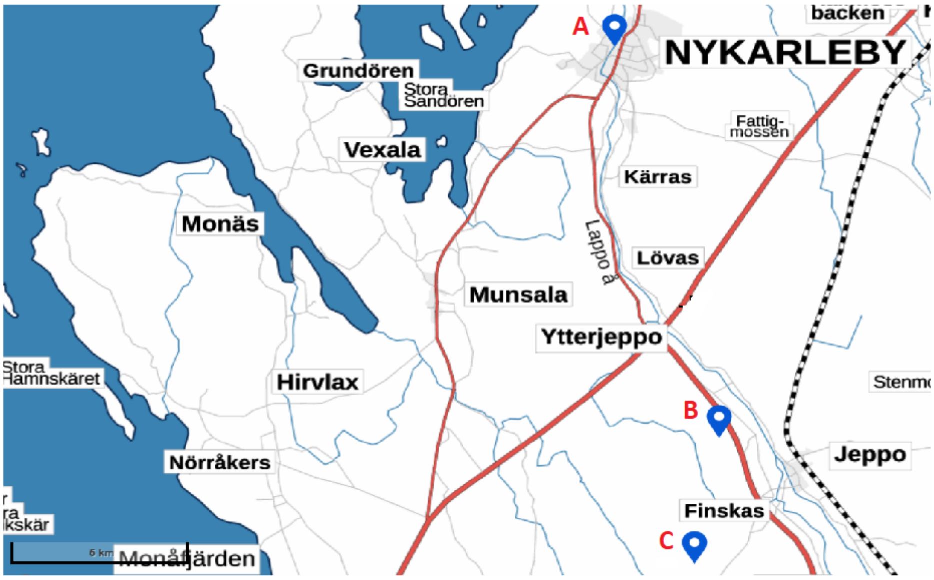


Figure 1: Locations of Renewable energy power plants in Nykarleby.
A) Stadsfors B) Jeppo Biogas C) Jeppo 1-2

3.1.1 Stadsfors -Hydro power plant

Nykarleby Kraftwerk is the oldest company in Nykarleby that has been producing electricity by using renewable energy. The first hydro power plant at the river Lapua started to operate in 1926 but Stadsfors was updated to its current state in 1984. The current Kaplan-turbine has power of 4.5 MW, which can be used when the flow of the river is 12-60 m^3/s. There is a new 2,1 MW turbine under construction and when it starts to operate it can exploit flow of the river also when it is 3-20 m^3/s. The head of the power plant is about 9.0 m. Today the hydro power plant produces about 20 % of the energy needed in Nykarleby and the new turbine could increase the production of the power plant by 10-20 %. (Riihimäki 2019, Nykarleby Kraftwerk 2020)

Alongside with power production Nykarleby Kraftwerk offers district heating, sewer and water services to its customers. There are about 5000 customers who get their electricity and about 3000 customers who get their water through the company. District heating business started in 2008 and heat is produced by the 3 MW storage water heater which mainly uses local wood chips as its fuel. (Nykarleby Kraftwerk 2020)

3.1.2 Jeppo Biogas

Jeppo Biogas (Jepuan Biokaasu Oy) is one of the companies in Nykarleby that produces renewable energy. Company is owned by other local companies and the biggest owner is a local grid company Jeppo Kraft Andelslag with 35 % share. Biogas plant was built in 2013 and today it produces $4.5 \cdot 10^6$ m^3 raw biogas yearly. Methane content of the biogas is 66.8 %. In one year, the amount of biogas produced is equivalent to 30 GWh of energy. (Jeppo Biogas 2019)

Material for biogas comes mainly from cow and pig manure with almost 75 % share. It is transferred to the plant by trucks but there is a 12 km long pipe system, which connects the biogas plant to 5 pig farms nearby. There are also biogas refuelling station for vehicles next to the biogas plant. (Jeppo Biogas 2019)

Customers of the Jeppo Biogas are using the final product for their own heat production. There is a gas network in Jeppo, which transfers biogas straight from the biogas plant to few local companies. The length of the gas line is over 6 km. (Jeppo Biogas 2019)

In the future Jeppo Biogas has plans to develop the manure production so that they could get revenue from processed manure products and have less water in the final product and lower transport costs. They also want to be able to digest dry and severely treated pulp. (Jeppo Biogas 2019)

3.1.3 Jeppo 1-2 -Wind power plant

At the moment there are two onshore wind turbines in Nykarleby, which are producing energy. They are both owned by EE Primus Oy and started to operate in 2017. Nominal power of the wind turbines is 6.9 MW combined. (Mikkonen 2019) Wind turbines are located about 16 km south from the centre of Nykarleby. Both are made by Vestas and the model is V126 – 3.45 MW. (Ethawind 2020)

Jeppo 1-2 –project was originally owned by Prokon, but it was sold to EE Primus in the spring 2016. EE Primus operates closely with Danish European Energy A/S because European Energy is its holding company. (CVM GmbH 2016) European Energy was founded 2004 and lately its business has been installing wind power and solar power (European Energy 2019).

3.2 Plans for the future

Future for renewable energy production looks promising, especially considering wind power. Capacity for wind power can be increased from the 7 MW up to 370 MW in the next few years. Locations for the planned projects are shown in figure 2.

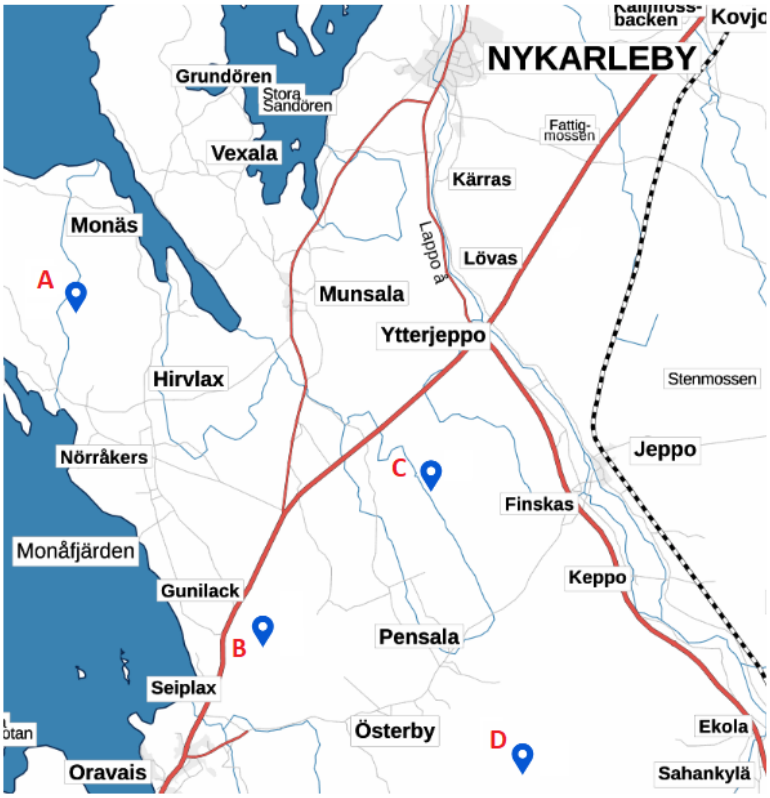


Figure 2: Locations of planned renewable energy power plants in Nykarleby. A) Kröpuln B) Sandbacka C) Björkbacken D) Storbötet 2

3.2.1 Kröpuln -Wind power plant

Kröpuln is an onshore wind farm project owned by OX2. Kröpuln is located about 20 km to the south-west from the centre of Nykarleby. OX2 is going to build 7 wind turbines in the area and maximum height for turbines is 203 m. All 7 turbines have nominal power of 30 MW combined. With this nominal power the produced energy could be 100 GWh yearly. (OX2 2019a) They are already building the wind turbines and the wind farm should be ready in 2021. Turbines will be made by Vestas and their model is Vestas V150 – 4.3 MW. (Ethawind 2020).

OX2 was founded 2004 and its headquarters is in Stockholm, Sweden. Today OX2 has already built 2.4 GW large scale onshore wind power in the Nordic countries. They also manage wind turbines which could provide yearly 5.9 TWh. (OX2 2019b)

3.2.2 Sandbacka -Wind power plant

Sandbacka is an onshore wind farm project owned by Svevind. It is located in the area of Nykarleby and Vöyri, about 20 km south from the centre of Nykarleby. Power plant should consist of 12-14 wind turbines and these turbines have nominal power of 49-74 MW. Wind power plant is fully permitted, and it should have been started to operate in 2020. (Suomen Tuulivoimayhdistys 2020) However, there have been problems in the execution of the project and the construction work has not been started yet.

Svevind is a Swedish company which concentrates onshore wind power projects. Its headquarters is in Piteå in northern Sweden. Svevind was founded in 1998. (Svevind 2020)

3.2.3 Björkbacken -Wind power plant

Björkbacken is an onshore wind farm project owned by Energiequelle. Project consists of up to 26 wind turbines and their maximum height is 280 m. (Energiequelle 2020a) Project is planned to be finished in 2024 and then the wind power plant should have nominal power of 100-150 MW depending on the number of wind turbines (Suomen Tuulivoimayhdistys 2020). Björkbacken is located about 14 km south from the centre of Nykarleby (Ethawind 2020).

Energiequelle was founded 1997 and it has been focusing on renewable energy projects. Its headquarters is in Kallinchen, Germany and today there are offices in three countries: Germany, France and Finland. In total, there are over 250 employees working for Energiequelle. (Energiequelle 2020b)

3.2.4 Storbötet 2 -Wind power plant

Storbötet 2 is an onshore wind power project owned by Prokon. Project is located about 23 km south from the centre of Nykarleby next to Storbötet 1 project. Storbötet 2 consists of 18 wind turbines and their maximum height is 250 m. (Prokon 2020a) Project is planned to be ready in 2025 and then it should have nominal power of 108 MW (Suomen Tuulivoimayhdistys 2020).

Prokon is a German company that concentrates wind power projects and in Germany it sells electricity straight to customers. Its headquarters is in Itzehoe, Germany and there are also offices in Finland and in Poland. It has been part of the wind power industry since 1995 and it has been part of building 365 wind turbines with a total of 674 MW nominal power. (Prokon 2020b)

4. SOLAR POWER

Interest in building new wind farms in Nykarleby from four different companies shows that the area has a great potential for wind power and building wind farms is a feasible solution. On the other hand, wind power does not fit everywhere and there is a need for other options to support wind power. One of them is solar power, which has been rapidly increasing its production globally in the recent years.

In 2019 power generation from solar power increased 22 % reaching a total amount of 720 TWh. Development of energy produced by solar power from the last two decades can be seen in figure 3. In the figure there is an estimation for the next decade and if the increase stays on average 15 % per year it will match the estimation. In this situation energy production from solar power will be almost 3300 TWh in 2030. (Bahar et al. 2020) This chapter concentrates on the radiation of the sun and how it can be used to generate electricity with photovoltaic cells.

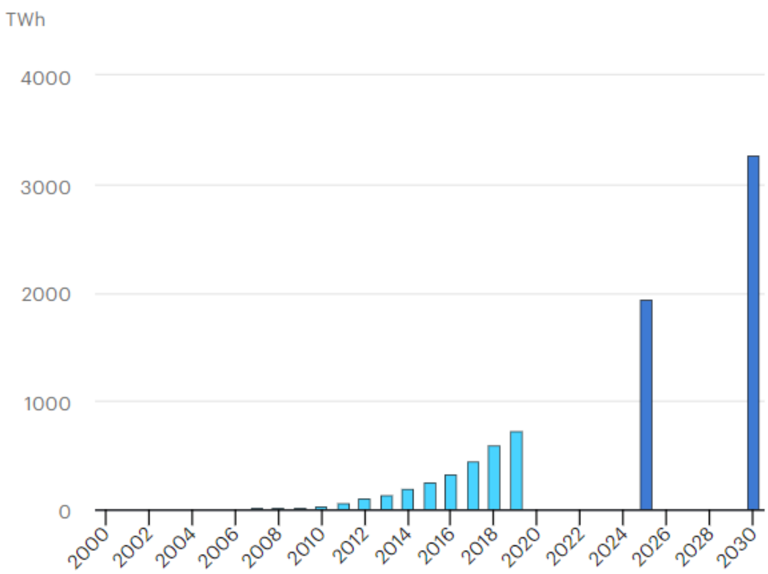


Figure 3: Energy production by solar power in 2000-2030 (Bahar et al. 2020)

4.1 Radiation and movement of the Sun

For people to be able live on earth, energy provided by the sun is necessary. Amount of energy that the sun provides to the earth for one hour would be enough to fulfil the energy need of the people on earth for a year. This section concentrates on radiation from the sun and other properties that are important for using solar power.

4.1.1 Radiation of the Sun

Radiation of the sun as an energy density per unit area can be calculated through Planck's blackbody radiation equation

$$\omega_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}}-1}, \tag{1}$$

where h is Planck's constant, c is speed of light in vacuum, k is Boltzmann's constant, λ is wavelength and T is temperature of blackbody in kelvin. Temperature on the sun's surface is about 5800 K. With this radiation the irradiance at the top of the atmosphere is 1367 W/m^2, which is called solar constant. All the radiation does not reach the surface of the earth because some of it is absorbed during its travel or reflected to the space. Figure 4 shows the difference between the blackbody spectrum and air mass (AM) 1 spectrum. AM 1 means the length which sunlight travels when its path is vertical and direct to the surface of the earth at sea level. The length is AM 0 when sunlight reaches the top of the atmosphere. Figure 4 shows the cumulative incident energy compared to wavelength.

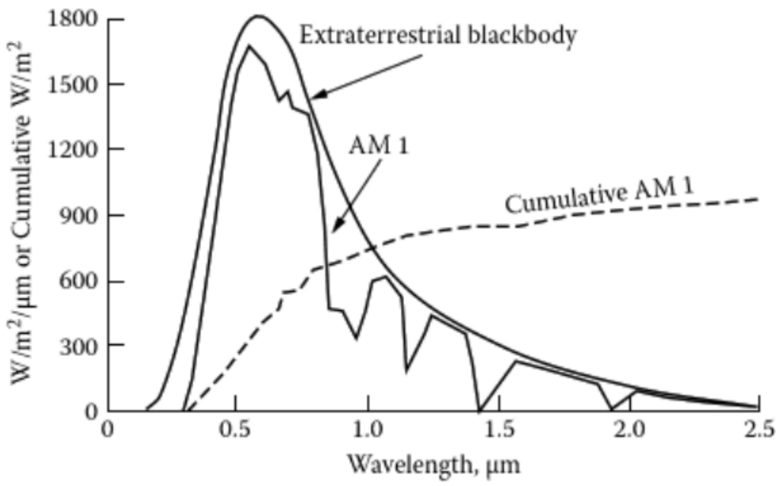


Figure 4: Blackbody spectrum, AM 1 spectrum and cumulative AM 1 compared to wavelength (Messenger et al. 2010)

As it can be seen from the figure there are differences between blackbody and AM 1 spectrums in every wavelength but for some wavelengths the difference is more significant. This causes the irradiance to drop to 1000 W/m^2 at sea level. Because irradiance gives the power density of the sun radiation, in some cases it is more useful to use energy density of the radiation which is called irradiation. Irradiation is measured in kWh/m^2. (Messenger et al. 2010)

4.1.2 Solar angles

The earth travels full lap around the sun in 365.25 days and at the same time it rotates around its own axis. This axis is a little bit tilted and the angle changes during the year. This angle is called solar declination. Solar declination means the angle between the plane of the earth's equator and the plane of earth where it travels around the sun. Maximum value for the declination is ±23.45° and these happen twice a year at time of winter or summer solstice. Similar way two times in the year declination is 0° at the time of spring or autumn equinox. (Brownson 2014)

Declination does not depend on the location of the observer like the other solar angles. Solar altitude angle (α_s) is the angle between the horizontal plane and the sun. Solar zenith angle (θ_z) is a similar angle, but it stands for the angle between the sun and vertical from the location of the observer. Together these create 90° angle. Solar azimuth angle (γ_s) is angle on the horizontal plane. It changes between 0-360° and when the angle 180° the sun is south from the observer. (Kalogirou 2014) These angles are shown in figure 5.

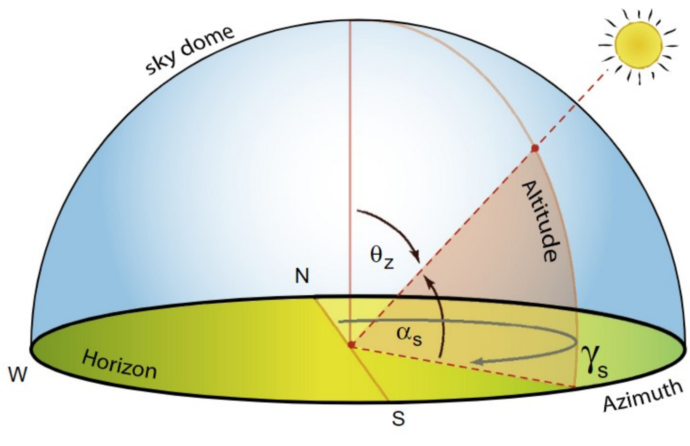


Figure 5: Altitude, Azimuth and Zenith angles (Brownson 2014)

4.2 Photovoltaic cell

Energy from sunlight can be transformed to electricity with photovoltaic cells. Producing electricity happens through the photovoltaic effect. Energy that one cell can produce is rather small, which is the reason why a solar panel consists of many photovoltaic cells. Structure of the cell can be seen in figure 6.

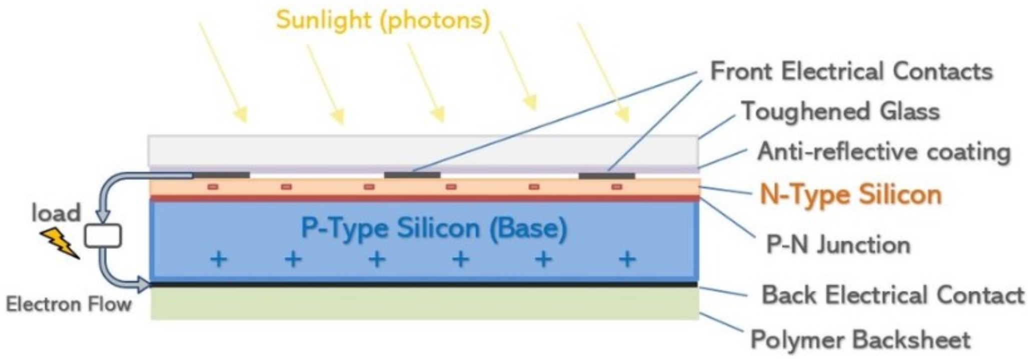


Figure 6: Structure of the photovoltaic cell (Svarc 2019)

The most important parts for the electricity production are the n-type and p-type semiconductors, which are usually made from silicon in photovoltaic cells, and the p-n junction between them. These two types of semiconductors are necessary for the function of the cell. Both types are electronically neutral, but n-type semiconductor has surplus electrons. On the other hand, p-type semiconductor has positive holes which are missing electrons. P-n junction does not have either surplus of electrons or free positive holes. State for the n-type can be achieved by doping the silicon (replacing silicon atoms) for example with arsenic or antimony. Similar way in p-type the doping of the silicon can be done with gallium or indium. (Kalogirou 2014)

Outside of the silicon parts there are electrical contacts. They made the connection to the load, which makes the current flow possible. For the other parts, the function is to keep the structure in a one piece and let as much sunlight as possible inside the cell. Figure 6 shows the structure silicon photovoltaic cell, which is the most used technology in solar modules. Thin film solar modules such as copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) have a small share of the energy produced by solar power. There are also other technologies under development such as perovskite and organic modules, but they have not been used commercially. (Fraunhofer ISE 2020a)

4.2.1 Photovoltaic effect

Photovoltaic effect is the key to electricity production from the photovoltaic cell. Figure 7 shows what happens when the sunlight reaches the cell. Sunlight consists of photons which are small particles without mass or electric charge. Photons can be absorbed by the cell but some of them are reflected away from the cell. Situation when the photon is absorbed is shown at the band diagram in figure 7.

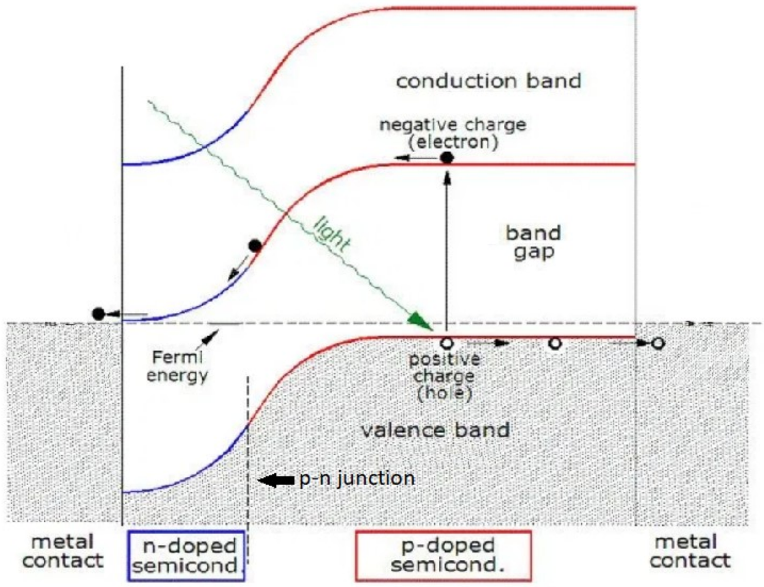


Figure 7: Band diagram of the photovoltaic cell (HiSoUR 2020)

Before any photons enter inside the cell, the valence band is full of electrons and on the other hand conduction band does not have any electrons. When the photon enters the cell with higher energy than the band gap (1.1 eV for silicon), the electron is released from the atom and it will jump from the valence band to the conduction band. If the energy is smaller than the band gap, the jump is not possible, and the energy of the photon increases the temperature of the cell. When the jump of the electron happens, it creates electron-hole -pair, where electron has a negative charge and hole has a positive charge. P-n junction creates an electric field inside of the cell, which separates two charge carriers from each other if they are close enough to the field. This causes electrons and holes to move in different directions and finally all the way to electrical contacts. Without electric field the electron moves back to the valence band, which is called recombination. If the electrical contacts are connected to each other with a load between them the current will flow if there is sunlight hitting the cell. (Kalogirou 2014, Messenger 2010)

Fermi energy shows the average energy of the electron and under equilibrium conditions it stays at the same level in the band diagram. Fermi level stays in the same distance from the valence and conduction band in the area where there is no electric field. These distances change when looking at the p-n junction where there is the field. The electric field can be seen in figure 7 at the point where the valence band and the conduction band are not horizontal. (Würfel 2005)

4.2.2 Cell characteristics

Photovoltaic effect explains what happens inside of the cell during energy production, but it is also important to know how different conditions affect cell characteristics. Current-voltage curve (IV-curve) is a one way to show characteristics of the photovoltaic cell. Example for the IV-curve for the cell is shown in figure 8 alongside a power-voltage curve (PV-curve).

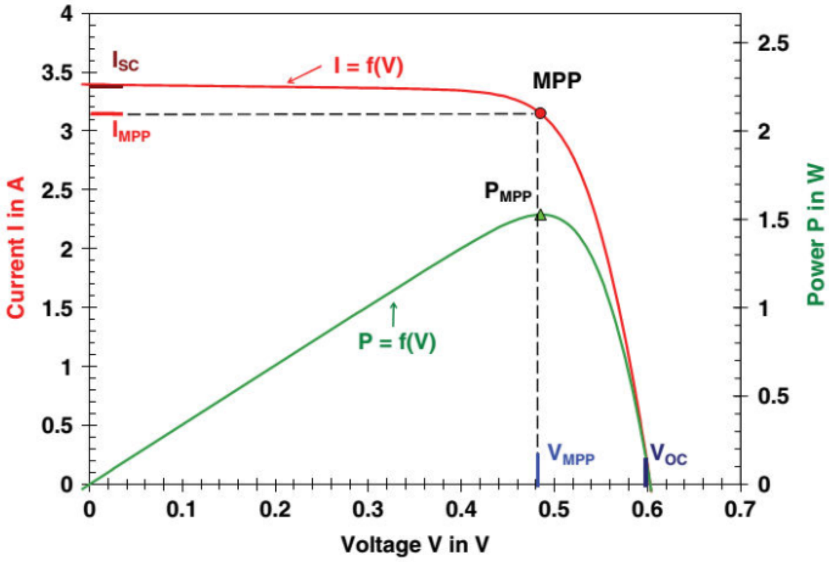


Figure 8: IV-curve and PV-curve for the solar cell (Al-Khazzar 2015)

IV-curve shows short circuit current (I_{SC}) and open-circuit voltage (V_{OC}) for the cell. These are the theoretical maximum values for the cell during its operation. Maximum power point (MPP) is on the IV-curve and it shows the voltage and the current which gives the maximum output power from the cell. These values can be used to evaluate the quality of the photovoltaic cell. This quality value is called fill factor (FF) and it is calculated with equation

$$FF = \frac{V_{MPP} I_{MPP}}{V_{OC} I_{SC}}, \quad (2)$$

where V_{MPP} is voltage at the MPP and I_{MPP} is the current at the MPP. This gives a percentage value how close to theoretical maximum the cell is operating. PV-curve shows the correlation between the voltage and the output power and the value of the output power at the MPP.

Conditions, where the photovoltaic cell operates, affects a lot to the shape of the IV-curve. The biggest factors are irradiance and the temperature. Figure 9 shows how the IV-curve changes with different irradiance levels.

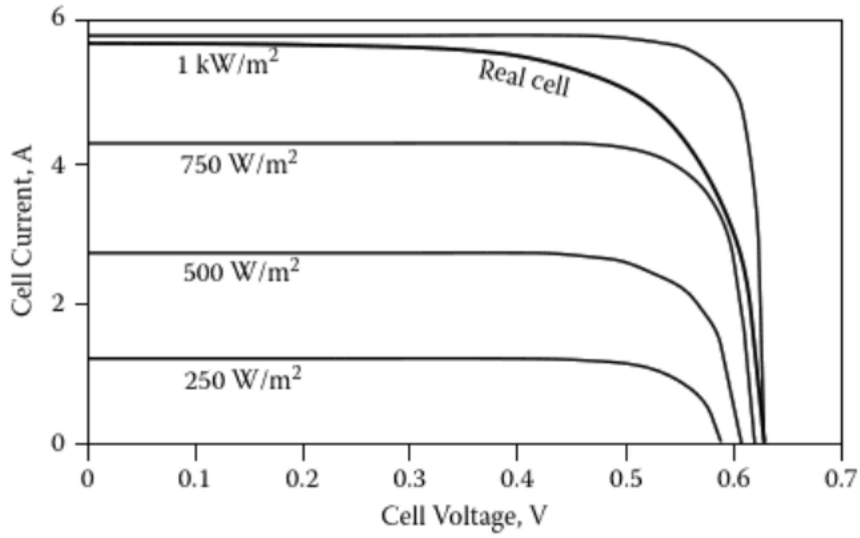


Figure 9: Photovoltaic cell under different irradiance level in ideal and real-life situation (Messenger 2010)

As it can be seen from the figure 9 irradiance does not have much influence towards the cell voltage. Voltage decreases slightly when the irradiance is also decreasing. On the other hand, irradiance has a significant effect on cell current. When the irradiance drops in half, pretty much the same thing happens to cell current and at the same time also the maximum output power drops a lot. Similarly, the effect of temperature towards IV-curve is shown in the figure 10.

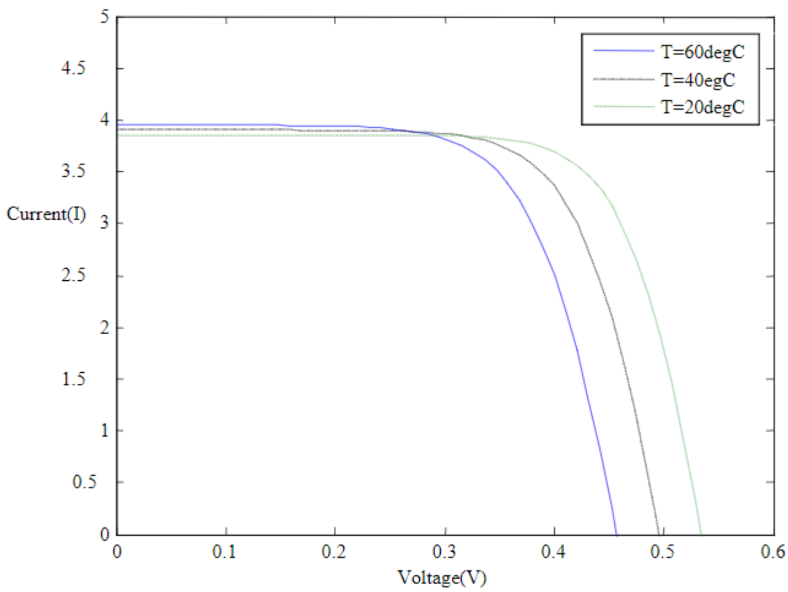


Figure 10: Photovoltaic cell under different temperature conditions (Kane et al. 2013)

Temperature does not have much effect on the cell current. When the temperature increases the current increases slightly. There is much greater difference when it comes to cell voltage. The cell voltage remains at a higher level in lower temperatures but when the temperature increases, the open-circuit voltage distinctly decreases which also lowers the maximum output power.

Values for the voltage and current for the one cell are low, so the cells need to be combined to increase both values and output power. This happens through series and parallel connections. When two cells are connected parallel the short-circuit current is doubled and the same happens for the voltage with series connection. (Gallegos et al. 2015) Cells can be connected in different ways inside the solar panel. When few cells are connected in series it is called a string and these strings are connected parallel to each other inside the solar panel. These connections play a role to the MPP of the panel when part of the panel under shading. Figure 11 shows IV-curve for the panel under different shading conditions. X over the cell means that the cell does not get any radiation. Measurements for the panel have been done 9th of January 2019 in Karlsruhe where the irradiance was 22.5 W/m^2.

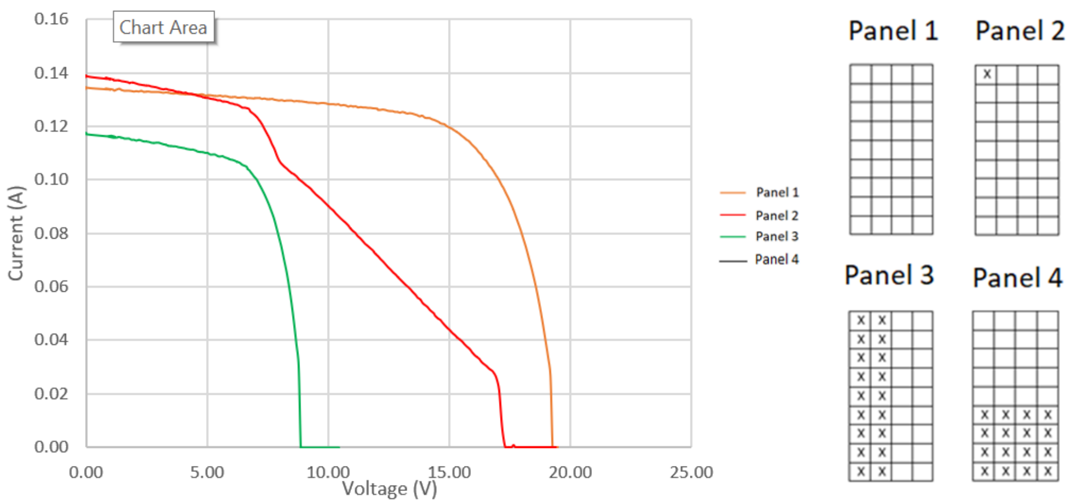


Figure 11: IV-curve of the solar panel under different shading conditions

When only one cell does not get the radiation, it drops MPP significantly even though I_{SC} and V_{OC} will not drop that much. Situation gets even worse with situation 3 and the output power goes to zero in situation 4. Situations 3 and 4 have similar numbers of cells under shading, but the latter does not produce any energy. This difference comes from the connections inside the panel. In this panel all the columns of cells are connected in series as strings and strings are connected in parallel. Figure 11 shows well how the production of the whole strings suffers when some part of it is under shading.

5. SOLAR POWER IN NYKARLEBY

Alongside with plans to increase production of wind power, solar power could be another option to increase the production from renewable energy in Nykarleby. This chapter concentrates on where a possible place for a solar power plant could be and what kind of energy production the location would offer. Evaluation for energy production potential has been done with PVsyst (V6.86)-software based on the chosen location. For the feasibility of the solar power plant, the financial side of the plant is also important. For a feasibility calculation it is essential to go through the investment and operation costs and what kind of incomes the power plant could provide.

5.1 Solar power plant

This section goes through a possible location for the power plant and how large the plant it is possible to fit there with effective layout. Section shows the power potential of the location and how much energy could be produced. It is also important to know how the power plant could be connected to the electric grid.

5.1.1 Location

Location for the solar power plant would be the area called Turuberget, which is located about 12 km south from the centre of the Nykarleby. Location is chosen because it would be close to the upcoming Björkbacken wind power plant. Area at the Turuberget has a size of 25 ha. Location of the plant is shown in figure 12.

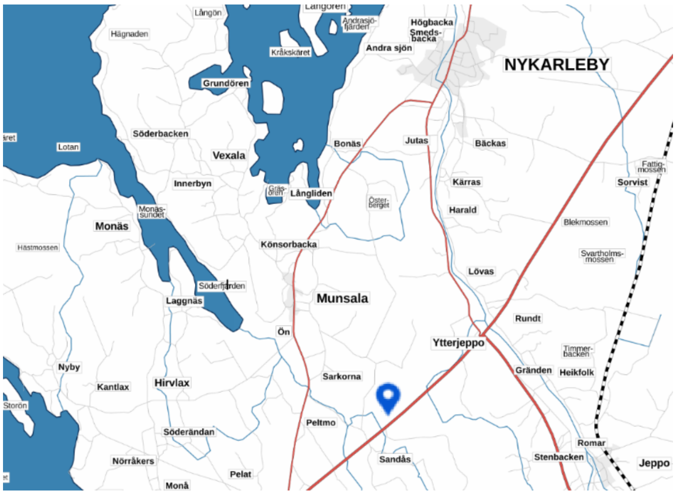


Figure 12: Location of the solar power plant

5.1.2 Characteristics

For the evaluation of solar power plant feasibility, the plant would be installed by using ground-mounted installation. Plant consists of 909 rows of modules which are 7.0 m apart and the width of the row is 4.06 m. This means that the total area of the modules is 135318 m^2. Modules are aimed towards the south with the azimuth angle of 180°. Modules are also tilted 25° up from the horizontal level.

There are many different models for modules and inverters that could be used for the evaluation but the chosen model for the modules is silicon monocrystalline RSM144-6-400M made by Risen Energy. Plant consists of 67425 modules with nominal power of 400 Wp. Modules are connected in strings where there are 25 modules in series and a total of 2697 strings are connected in parallel. Model of the inverters is SG250HX made by Sungrow. There are a total of 1107 inverters which have nominal power of 225 kW and operating voltage is 600-1500 V. With these components the power plant can reach the nominal power of 26 970 kWp. All the characteristic values have been chosen in a way that there would be maximum energy production per kWp. In the same area, it would be possible to fit more modules, which would increase the total amount of produced energy, but it would decrease the amount of produced energy per kWp and increase the investment costs.

5.1.3 Grid connection

Fingrid has plans to reinforce the grid in Ostrobothnia because of the increasing number of plans for wind power plants. One of the new substations would be a 400/110 kV substation of Jussila. (Fingrid 2017) Björkbacken wind power plant would be connected to this substation and the same connection point could be used also for the solar power plant. Solar power plant would be connected to 110 kV side to its own connection point or by using the same connection point with Björkbacken. Jussila substation would be located about 1.5 km east from the power plant.

5.1.4 Energy potential

The most important aspect for energy that can be produced is the irradiation that takes place in Nykarleby. Irradiation levels are based on the information from the Meteonorm-software from the years 1991-2010. Table 1 shows different irradiation values and average temperatures for different months and gives a total value for the year.

Table 1. *Irradiation and temperature values during a year in Nykarleby*

	Average temperature (°C)	*Horizontal Global irradiation (kWh/m²)*	*Horizontal Diffuse irradiation (kWh/m²)*	*Global irradiation in module surface (kWh/m²)*	*Global irradiation in module surface with losses (kWh/m²)*
January	-5.0	5.7	4.1	14.7	8.8
February	-6.8	21.7	11.7	43.2	32.6
March	-3.4	62.5	28.1	95.7	88.9
April	3.6	110.5	54.1	137.4	131.7
May	9.0	153.0	69.0	170.2	163.4
June	13.5	166.8	78.1	174.6	166.8
July	17.1	158.6	77.4	168.3	160.7
August	15.4	120.5	59.3	141.1	135.2
September	10.0	69.9	31.2	98.9	94.4
October	4.6	28.5	16.7	48.9	39.6
November	0.0	7.6	5.2	16.9	11.1
December	-3.4	2.7	2.0	9.5	4.4
Total	**4.6**	**908.0**	**436.8**	**1119.4**	**1037.8**

Horizontal Global irradiation means the total irradiance that reaches the surface of the earth. It consists of direct, diffuse and reflected irradiance. Horizontal Diffuse irradiance is created when photons, which are part of the direct irradiance, are scattered in the atmosphere. (Badescu 2008) It can be seen from the table 1 June is the best month for horizontal global irradiation with 47 % share of the diffuse irradiation. Relation between irradiation types stays close to the same value from March to September when there is most irradiation. But the share of the diffuse irradiation increases distinctly from October to February.

Benefits from tilting the modules in the right angle and direction can be seen, when comparing the global horizontal irradiation to global irradiation in the module surface. Irradiation suffers from some losses which is why the irradiation level is less than the global irradiance in the module surface. In this case the losses are caused by shading and reflections. Reflections mostly happen when the photons reach the air-glass-surface at the top of the module. Shading losses are shown in the Iso-shading loss diagram in the figure 13.

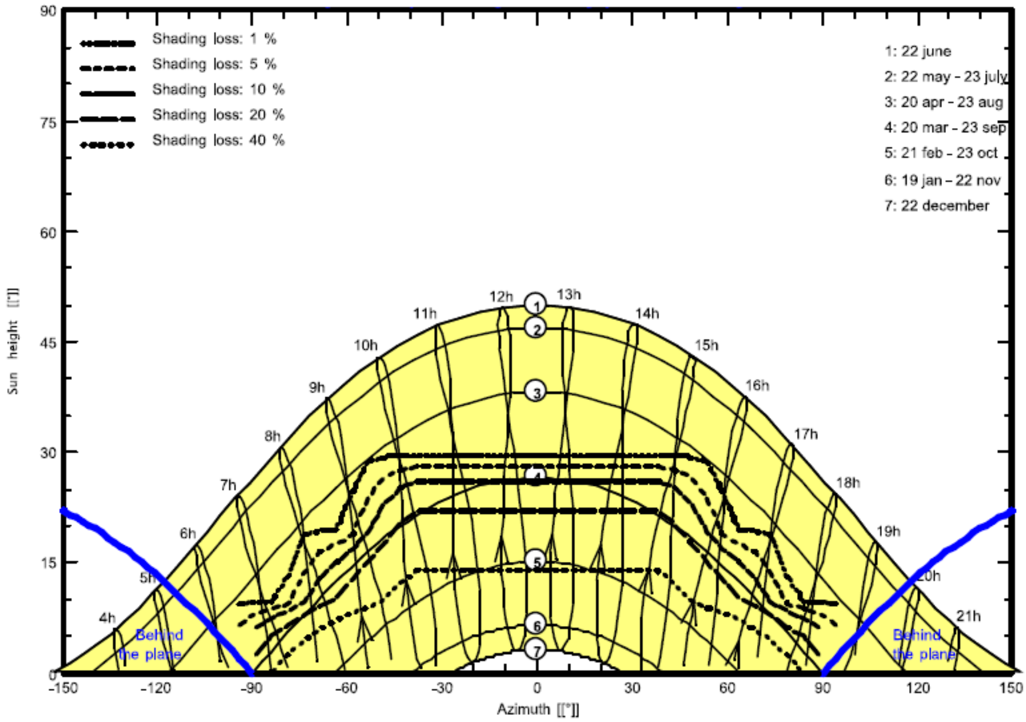


Figure 13: Position of the Sun in the sky during the year and height of the sun effect on shading losses at the power plant

Figure 13 shows the location of the sun during the year with altitude and azimuth angles. Time frames in the right top corner correspond to the numbers from 1 to 7 in the figure. Time frame 1 is only one day and time frames 2-6 show the first and the last day of the time frame excluding the previous time frames. At the end, the time frame 7 is again only one day. Lines where each number is located show the location of the sun during the day, when it is above the horizon. As it can be seen on 22nd of June the sun rises above the horizon before 4 am and goes down after 9 pm in the evening and the maximum altitude angle is around 50°. On the other hand, with a time frame 7 sun rises after 10 am and goes down before 3 pm, when the maximum altitude angle stays around 5°.

Dashed lines show the different percentage of losses caused by shading. Values for the shading are shown in the top left corner. This shading is caused by another row of modules in the power plant. When the line, where is the time frame number, drops below dashed lines, there is some shading losses. For example, in the time frames 1 to 3 there isn't any shading loss because the Sun stays high enough during the whole day. On the other hand, in the time frame 4 the shading loss varies both sides of 20 %, which is shown by the second lowest dashed line. This shading is caused by other row of modules in the power plant. Blue lines show the limit when the azimuth angle of the sun is too large or too small and then the rays of the sun are parallel to the surface of the module. With those limit values or beyond them sun radiation does not hit the surface of the modules.

When characteristics of the power plant and the solar radiation in Nykarleby are put together, it is possible to estimate energy production by using the previously mentioned PVsyst-software. Energy produced in the power plant which can be fed to the grid is shown in the table 2. It gives the values for different months and the total value for the whole year. In the same way, the table shows the performance ratios. Values are calculated based on the irradiation values from table 1.

Table 2. *Produced energy which could be injected to the grid and performance ratio of the power plant for every month*

	Energy to the Grid (MWh)	*Performance Ratio (%)*
January	212	53.8
February	809	70.0
March	2232	87.1
April	3400	92.4
May	4026	88.3
June	4074	87.1
July	3879	86.0
August	3303	87.4
September	2279	86.0
October	955	73.0
November	266	58.8
December	100	40.0
Total	**25533**	**85.1**

Performance ratio can be calculated with equation

$$PR = \frac{\frac{E_{Grid}}{P_{nom}}}{\frac{Irr_{mod}}{Irr_{ref}}}, \quad (3)$$

where E_{Grid} is energy fed to the grid, P_{nom} is nominal power of the power plant, Irr_{mod} is the global irradiance in the module surface and Irr_{ref} is reference irradiation at STC conditions, which is 1000 W/m^2. Total production for the year is 25533 MWh and best months are May and June with over 4000 MWh, but April has the best performance ratio. In April, the production is at a high level but compared to May and June the average temperature is clearly lower, which increases the operating voltage of the power plant and explains the better performance ratio. The total yearly production of 25533 MWh would mean that the efficiency of the modules would be 18.2 %. When the total production is compared to the size of the power plant, the production is 947 kWh/kWp for every year. For comparison, the same number for Hanko is 974 kWh/kWp. (Energiequelle 2020c) Even though Hanko is located about 400 km south from Nykarleby there is not much difference with these numbers.

5.1.5 Permits and town planning

The regional land use plan of Ostrobothnia 2040 states the first guidelines and restrictions, how the land in Nykarleby should be used. It shows for example, if the land has been reserved for specific use or if it should be protected for some reason. For the area of Turuberget there are not any guidelines or restrictions on how it should be used. Plan states that in 2040 different forms of renewable energy should cover the energy need in Ostrobothnia. This would be mostly covered with wind power and bioenergy. There are not any specific areas, which are reserved for solar power in the regional land use plan, instead the decisions for land use should be made at municipality level. (Pohjanmaan liitto 2020)

Solar power plant takes about 25 ha area in Nykarleby and in this scale of case planning requirement decision is not probably enough for town planning. Instead, there is a need to make changes to the local master plan. After changes to the local master plan, the construction permit for the solar power plant could be applied. (Isaksson 2020)

5.2 Investment costs

Investment costs are the part of the costs that takes place before the solar power plant can start to operate. Estimation of prices for different segments of the solar power plant are shown in the table 3. On the top of that grid connection fee is explained on the sub-section.

Table 3. *Investment costs of solar power plant (Energiequelle 2020c, Oikarinen 2020)*

Section	*Total price for the section (€)*	*Section price per MW (€/MW)*
Modules	7,800,000	280,000
Mounting structure	5,600,000	207,000
Inverters	1,200,000	44,000
DC Cables, connections, safety switches	230,000	8,500
Construction	4,200,000	155,000
Planning	400,000	15,000
Total	**19,430,000**	**710,000**

5.2.1 Grid connection fee

Connection to the grid is one essential matter for the power plant. Power plants in Finland are connected 110 kV, 220 kV or 400 kV grid depending on the size and the location of the power plant. When the size of the power plant is below 250 MW, it is connected to either 110 kV or 220 kV substation. If it is over 250 MW, connection is made to 400 kV substation. Table 4 is showing the connection fees into the Fingrid's substations which are already existing. (Fingrid 2020a)

Table 4. *Fingrid connection fee (Fingrid 2020b)*

Substation type	*Connection fee (M€)*
400 kV substation	2.0
220 kV substation	1.2
110 kV substation	0.6

5.3 Operation costs

Operation costs are the part of the costs that takes place during the operation of the power plant. Estimation of the costs for different segments of the solar power plant are shown in the table 5. Rest of the costs come from grid fees and taxations and they are explained in the subsections.

Table 5. *Operation costs (Energiequelle 2020c, Ministerie van Landbouw 2020)*

Cost type	*Costs per year*	*Costs for 30 years (€)*
Land leasing	900-2,000 €/ha	20,700-46,000
Maintenance, Insurance, Surveillance etc.	4,500-6,000 €/MW	135,000-180,000

5.3.1 Grid service fee

After the connection to the grid has been accomplished, grid creates costs based on the use of the grid. One fee takes into account how much energy is fed to the grid and the other is based on the capacity of the power plant that is connected to the grid. Table 6 shows grid service for 2020 in Fingrid's grid.

Table 6. *Fingrid's service fee 2020 (Fingrid 2020c)*

Type of fee	*Service fee*
Use of grid, input into the grid	0.60 €/MWh
Generation capacity fee for power plants	158.33 €/MW/month (1900 €/MW/year)

5.3.2 Property tax

Solar power plants are part of the property taxation whether installed on the wall or at the rooftop of the building or as a standalone system on the ground. Plants that are attached to the building will not change the repurchase value of the building and then the property tax of the building does not change with possible exception of summer houses if the summer house is electrified due the power plant. For a standalone power plant also ground where it is installed is part of the property taxation and there the taxation goes with public property tax. (Auvinen et al. 2016, Verohallinto 2020)

Public property tax is used for power plants that have nominal power of 10 MVA or less. In Nykarleby public property tax is 1.0 %. Above 10 MVA power plants there can be used an own property tax for power plants if municipal council has decided so. According to KiVL 14 § clause 1 this power plant property tax cannot be higher than 3.1 %. In Nykarleby it is 3.1 % in 2020. (Verohallinto 2020, Nykarleby 2019)

Property tax is based on the replacement value of the building which is 75 % of the construction costs. Although, in the case of solar power plants solar panels and possible motors that can be used to turn them towards the wanted direction are excluded. This would mean that the replacement value of the solar power plant would be based on the material and construction costs of the foundations and the mounting structures of the solar power plant. For the right value for the property tax also age discount needs to be considered. For solar power plants there is no statute for age discount but for wind power plants it is 2.5 % and this could be a reasonable value also for solar power plants. Age discount is counted from the replacement value and so for the first year it is 2.5 %, 5.0 % for the second, 7.5 % for the third et cetera. (Auvinen et al. 2016)

5.4 Incomes

Incomes from the solar power plant come from selling the electricity to the customers. With a power plant that produces a lot of energy, selling the electricity can be done with power purchase agreement (PPA). PPA means a contract between two sides: producer and customer. PPA specifies the terms of the contract, how long does it last, amount of electricity that should be supplied and what is the price paid for the electricity. These are the main aspects for the PPA, but terms may vary based on the needs of the companies. (Next 2020)

PPA contracts are usually long-term deals such as 10 or 20 years. After that incomes are based on the market price of the electricity. Market price estimation is made by Energiequelle and it is based on reports from Pöyry and Energy Brainpool. Estimation shown in the figure 14 is has been made from Q2 2020 reports.

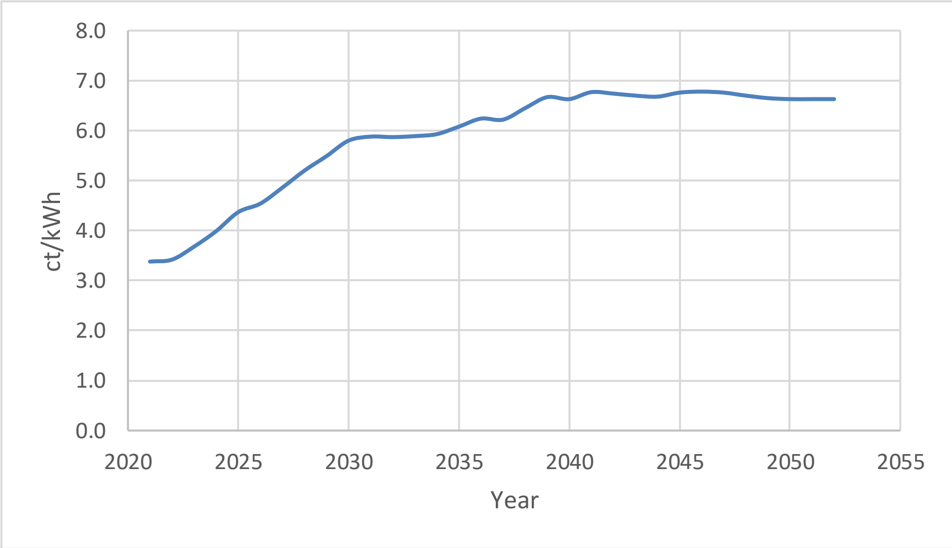


Figure 14: Price estimation for electricity in Finland 2021-2052 (Energiequelle 2020c)

Estimation shows clearly that electricity price should increase during the next decades, which also affects solar power plant incomes because of its operation time which is 30 years. Prices shown in figure 14 have been reduced by 20 %, so possible inaccuracies in the estimation would not affect the feasibility calculations.

5.5 Feasibility

All the aspects from the previous sections come together to calculate how feasible the solar power plant would be in Nykarleby. First subsection concentrates on the current situation with two different kinds of business models. Second part considers how the feasibility would change when altering the PPA-deal, efficiency and price of the modules.

5.5.1 Current situation

Here it is considered two types of business models. In the model 1 a builder company builds the power plant and then sells it to the investor. The builder gets the possible profit from difference of the investment cost and selling price. The investor gets its own profit during the operation of the power plant by selling the electricity. In the model 2 the builder company does not sell the power plant, instead it operates the power plant for its whole lifetime. Starting values for both models are shown in table 7. Values are chosen or calculated based on the information presented previous in this chapter and are compiled to this table.

Table 7. *Values for the feasibility calculation*

Sector	*Values for the power plant*	
Operation time	30 years	Years 2022-2051
Energy production	25533 MWh/a	0.3 % yearly decrease during the operation
PPA-deal	10-year: 3.0 c/kWh and 0.19 c/kWh balancing costs	after the year 10 based on the electricity market price
Incomes	35,498,000 €	7,484,000 € (PPA) 29,203,000 € (Market)
Investment costs	20,030,000 €	
Operation costs	417,680 €/a (1. Year) 9,847,000 € (total)	Land lease 1500 €/ha/a, Maintenance 5000 €/MWp/a, Property tax 179,000 €/a (1. Year)

Feasibility calculations are made based on the values from the table 7 and results for the model 1 are shown at the table 8. Figures are based on the calculations, which are made by Energiequelle's own calculator. Calculator also gives the estimation for the selling price, which is based on the financing cost and PPA-deal of the power plant and the estimated market price of the electricity. Financing costs of the investor includes the interest from the loan. They are based on that the investor would have 37.69 % of own capital for the purchase and the rest is financed with a loan. Loan has 2.5 % interest, and it will be paid back evenly within 20 years with the exception that for the first year the only cost is the interest.

Table 8. *Model 1: Results for the feasibility calculation*

Model 1	*Key figures*
Selling price to investor	11,914,000 €
Builder's profit	**-8,230,860 €**
	-69.1 %
Investor's financing cost	1,879,000 €
Investor's profit	12,084,000 €
Payback time for the investor	**18.8 years**

As it can be seen from the table 8, model 1 does not make sense for the builder at all and it would not be feasible in their point of view with this selling price. On the other hand, for the investor the deal would be profitable, and they would get their money back in under 19 years.

With the model 2, the solution would be that the builder takes a similar loan with the same share of own capital and interest than the model 1. Results for model 2 are shown at table 9.

Table 9. *Model 2: Results for the feasibility calculation*

Model 2	*Key figures*
Financing cost of the builder	3,530,162 €
Builder's profit	5,266,803 € (26.3%)
Payback time for the builder	**21.6 years**

With the model 2 builder makes a profit which is over fourth of the investment costs which makes model 2 clearly a feasible solution. This means also that solar power would be a profitable solution if the builder could use the produced energy on their own. This could be possible for bigger companies and shopping centres.

5.5.2 Future development

Solar power is a developing technology, and its characteristics are still changing. This subsection shows how the situation would improve, when either PPA-price, efficiency of the modules or module price would change while the other two would remain the same than the current situation. Model 2 shows already in the current situation that it would be a feasible solution for a solar power plant. There is no reason to assume that the model 2 would not be feasible also in the future and this is the reason why the future development analysis concentrates on only to the model 1. Table 10 shows how the situation with model 1 changes when PPA-price is increasing. Table shows selling price and profits for both builder and investor. Cell for the profits shows first the profit for the builder and then for the investor.

Table 10. *Selling prices and profit values for the builder and the investor in the model 1 with different PPA-price*

PPA-price	*Selling price (€)*	*Profits Builder/ Investor (€)*
4 c/kWh	13,654,000	-6,513,135 12,463,000
5 c/kWh	15,849,000	-4,340,410 12,387,000
6 c/kWh	18,044,000	-2,167,685 12,311,000
7 c/kWh	20,239,000	4,965 12,233,000
8 c/kWh	22,434,000	2,177,690 12,157,000

Numbers in table 10 show the situation when the price for the PPA-deal increases but everything else stays the same compared to the current situation. Increasing the price increases the selling price and because of that the profit for the builder improves. With 7 c/kWh price builder makes its money back and with 8 c/kWh builder makes 10 % profit compared to investment costs. Prices for PPA-deal are low at the moment, but market price for the electricity is estimated to increase as it can be seen from the Incomes-subsection. This would indicate that also PPA-prices could increase. Probably they will not increase to 7-8 c/kWh level but something like 5-6 c/kWh could be possible.

Table 11 shows how the selling price and profits for the builder and investor would develop in the model 1, when the efficiency of the modules increases, which also improves the production. When the production improves, the selling prices increase and the financial side also looks a bit better than the current situation, but even with 16.5 % improvement model 1 is not feasible for the builder.

Table 11: *Selling prices and profit values for the builder and the investor in the model 1 with efficiency increase*

Efficiency increase	*Production increase*	*Selling price (€)*	*Profits Builder/ Investor (€)*
+ *0.3 %*	+ 1.6 %	12,194,000	-7,953,635 12,322,000
+ *1.5 %*	+ 8.3 %	13,324,000	-6,834,885 13,316,000
+ *3.0 %*	+ 16.5 %	14,729,000	-5,443,910 14,565,000

Increase of the efficiency has been lately about 0.3 % per year for silicon-based modules If the development stays the same, 3 % increase for the efficiency could be reached in 10 years. There are other technologies, which could improve the efficiency faster in the future. In the figure 15 shows how the efficiencies have been improving in laboratory testing during the last 25 years. Mono crystalline silicon and Multi crystalline silicon are the most widely used technologies in the commercial market with over 90 % share in year 2019 but few technologies have passed them in laboratory circumstances. (Fraunhofer ISE 2020a)

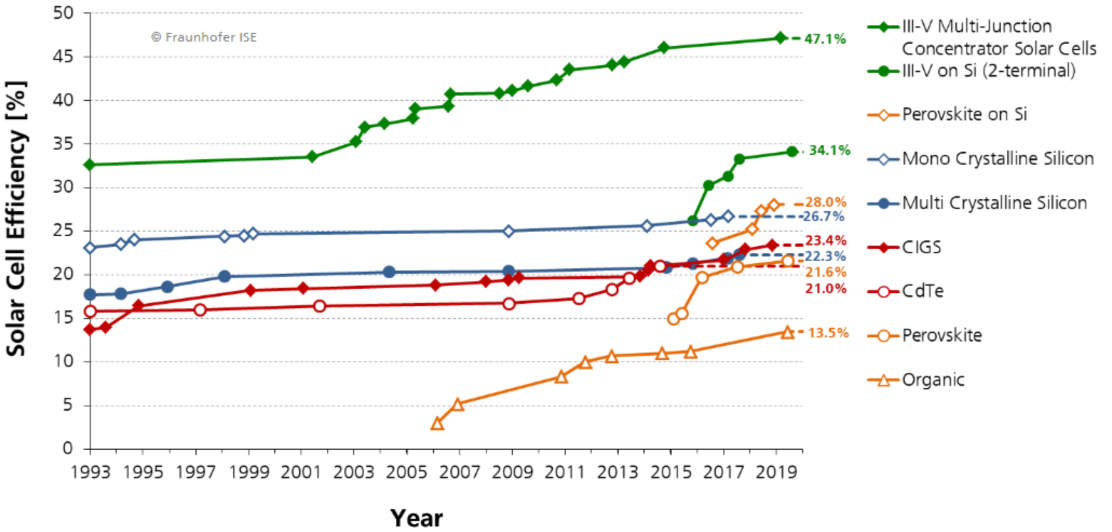


Figure 15: Development of Laboratory Solar Cell Efficiencies (Fraunhofer ISE 2020a)

Alongside with the efficiency, the prices of the modules are decreasing while the technology is more developed. Figure 16 shows how the module and inverter prices have changed during the last 15 years.

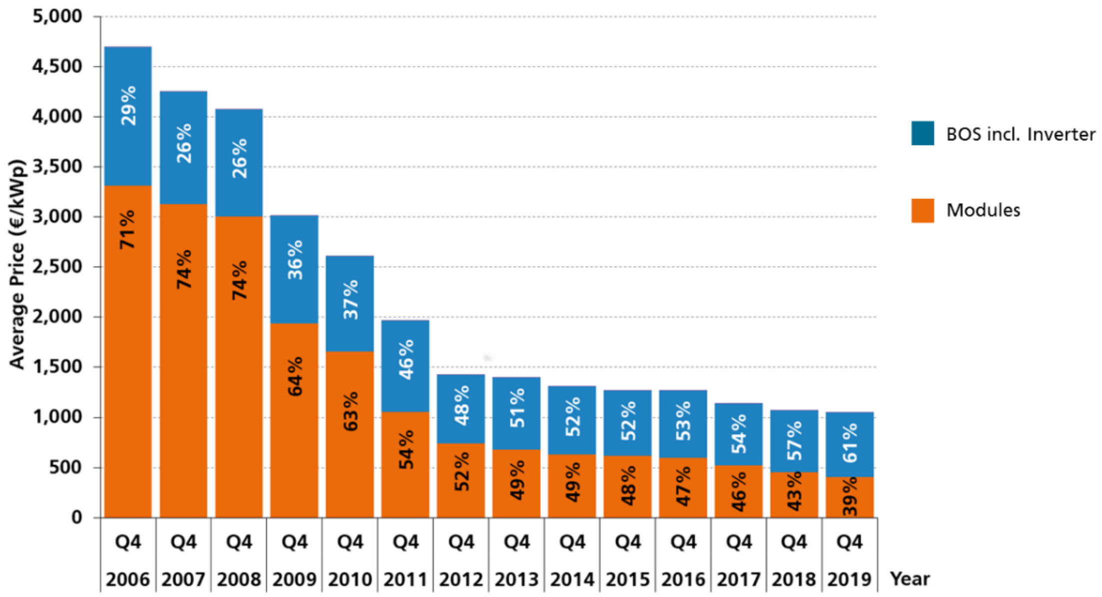


Figure 16: Price development of the modules and inverter (Fraunhofer ISE 2020b)

Prices for the modules and their share of the module-inverter combination has been decreasing every year since 2006, but the decreasing has slowed down in recent years. Table 12 shows how the module price decrease would affect the power plant profits and selling price with model 1 in Nykarleby. In the profit column, the first number is the builder’s profit and the second one is for the investor.

Table 12: *Selling prices and profit values for the builder and the investor in the model 1 with different decrease of module prices*

Module price decrease	*Selling price (€)*	*Profits Builder/ Investor (€)*
-1 %	11,924,000	-8,143,010 12,086,000
-5 %	11,964,000	-7,791,385 12,099,000
-10 %	12,009,000	-7,356,910 12,118,000

Table 12 shows that the decreasing just the module prices does not make much difference for the selling prices or the profits. Even with the 10 % decrease the model 1 is not feasible for the builder. Development of each sector does not happen independently from the others. Instead, they develop alongside each other. Table 13 shows the best-case scenario for the model 1.

Table 13: *Best-case scenario for the model 1*

Best case scenario	*Selling price (€)*	*Profits Builder/ Investor (€)*
5.5 c/kWh *+ 3 % efficiency* *-10 % module price*	20,704,000	1,245,165 14,888,000

With 3 % efficiency increase and 10 % module price decrease the power plant would need 5.5 c/kWh PPA-deal for the power to be feasible in Nykarleby. If the development of the technology remains like it has been recent years, efficiency and price goals can be reached in the future. The biggest question for the feasibility of the model 1 is how PPA-prices and electricity market prices develop in the future.

6. ENERGY STORAGE SYSTEMS

Role of energy storage systems is going to become even more meaningful for the energy supply in the future. Reason for this is the increasing use of renewable energy as part energy production. Renewable energy such as wind or solar power has a great potential for energy production, but they are dependent on the weather. With energy storage systems it is possible to secure more stable energy production even if there is no solar or wind power available. Storage system also helps to better match the energy demand and decrease peak prices of the electricity.

There are many different methods to store the energy. This is necessary because there are also different kinds of needs for energy storage such as how much and how long energy needs to be stored and how fast it needs to be able to supply to the grid. Table 14 shows these characteristics for different kinds of energy storage systems.

Table 14: *Characteristics of different energy storage systems (Deloitte 2015, Evans 2012)*

Technology	*Power rating (MW)*	*Discharge time*	*Cycling or lifetime*	*Self-discharge (%)*	*Energy density (Wh/l)*	*Power Density (W/l)*	*Efficiency (%)*	*Response time*
Supercapacitor	0.01-1	ms-min	10,000-100,000	20-40	10-20	40 000-120 000	80-95	10-20 ms
SMES	0.1-1	ms-min	>100 000	0-15	~6	1 000-4 000	80-98	<100 ms
PHS	100-1 000	4-12 h	30-60 years	~0	0.2-2	0.1-0.2	70-85	sec-min
CAES	10-1 000	2-30 h	20-40 years	~0	2-6	0.2-0.6	40-89	sec-min
Fly wheels	0.001-1	sec-hours	20,000-100,000	1.3-100	20-80	5 000	70-95	10-20 ms
NaS battery	10-100	1 min - 8 h	2,500-4,500	0.05-20	150-300	120-160	70-90	10-20 ms
Li-ion battery	0.1-100	1 min - 8 h	1,000-10,000	0.1-0.3	200-400	1 300-10 000	85-98	10-20 ms
Flow battery	0.1-100	1-10 h	12 000-14 000	0.2	20-70	0.5-2	60-85	10-20 ms
Hydrogen	0.01-1 000	min - weeks	5-30 years	0-4	600 (200 bar)	0.2-20	25-50	sec-min
SNG	50-1 000	hours - weeks	30 years	negligible	1 800 (200 bar)	0.2-2	25-50	sec-min

Table 14 shows the characteristics for different kinds of storage systems. Supercapacitor, superconducting magnetic energy storage (SMES) and flywheel have similar properties. They all have high power density, and it is possible to get the energy quickly out of the storage. At the other end of the scale there are pumped hydro storage (PHS), Compressed-air energy storage (CAES), hydrogen and synthetic natural gas (SNG), which can be used to store large amounts of energy for longer periods of time. At the table there are three different kinds of batteries, which fit in the middle of the first two groups with their properties. Power ratings stay lower than for example PHS but also energy from the storage can be used faster.

Alongside with the information at table 14, storage capacity is one important factor for energy storage technology and how it can be used. In the figure 17 it is shown storage capacity compared to discharge time.

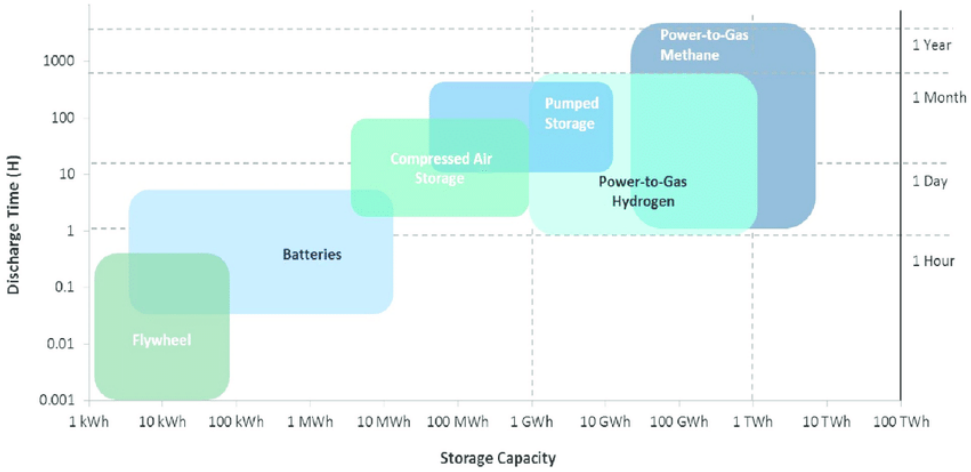


Figure 17: Discharge time of the storage systems compared to storage capacity (Moore et al. 2016)

With batteries and flywheels, it is possible to get energy out of the storage much faster compared to PHS and hydrogen. On the other hand, storage capacity potential for PHS and hydrogen is larger, and they have longer discharge time so they can maintain their output power for longer time.

When it comes to installations of energy storage systems some of them have been more widely used. Lithium-ion batteries have increased their share of installed energy storage systems and lately it has been the most popular solution. Shares of the installed energy storage systems are shown in the figure 18 excluding the pumped hydro storage.

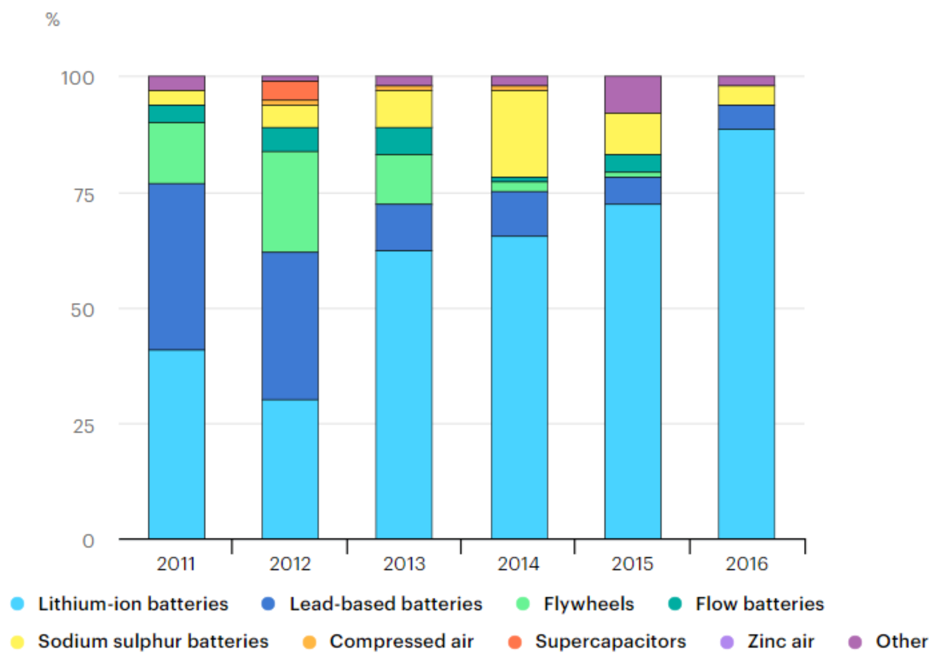


Figure 18: Shares of installed energy storage technologies excluding pumped hydro storage (IEA 2020)

Pumped hydro is an effective way to store a lot of energy, but it has specific requirements for the location, and it cannot be built everywhere.

In 2011 and 2012 lithium-ion batteries’ share of installed energy storage capacity was just 41 % and 30 % respectively but after that the share has been increasing. In 2018 share of installed energy storage capacity was already over 88 %.

This chapter concentrates on two of those technologies mentioned at table 14, which could be used alongside wind power and solar power. These two are batteries and power to gas –concept, which uses hydrogen. Batteries, especially lithium-ion, have been lately the most popular solution to combine with renewable energy. On the other hand, power to gas –concept with the use of hydrogen could be a potential solution for storing a large amount of energy for a longer period but it has not made the commercial breakthrough on a larger scale.

6.1 Battery

Battery is an electrochemical solution to store energy where chemical energy is converted to electrical energy during the discharge. This section explains functionality of the battery.

6.1.1 Structure and redox reaction

The simplest battery is just one electrochemical cell but usually the battery consists of many cells. There are two different electrodes in an electrochemical cell and an electrolyte between them. There is also a separator in the electrolyte which blocks short circuits between electrodes. Structure of the battery is shown in figure 19. To get the current to flow there a need to be a connection between two electrodes via wire. Current flow is happening due the electromotive force. Electromotive force is a potential difference between the two electrodes. Electromotive force causes redox reactions to happen at both electrodes and this generates electrons which go through wire connection between two electrodes. Same time when the electrons move through the wire also ions travel through the electrolyte from one electrode to another. Redox reactions keep happening until the cell reaches electrochemical balance. (Park 2020, Crompton et al. 2000)

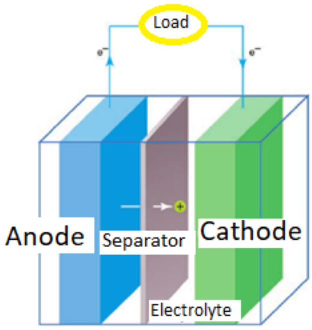


Figure 19: Structure of battery during discharge (Park 2012)

General equation for redox reaction (oxidation/reduction reaction) is

$$aOx + ne^- \rightleftarrows bRed, \tag{4}$$

where *a*, *b* and *n* are coefficients which are used to balance the equation. Values of coefficients are depending on the materials which are part of the reaction. The electrode where the oxidation reaction happens is called anode and the electrode where reduction reaction happens is called cathode. With a primary battery where the battery is used only once while discharging, the cathode is always the positive electrode and anode the negative electrode. On the other hand, with a secondary battery which can be charged and discharged for multiple times, roles of the electrodes change depending on how the battery is used. Roles of the electrodes are shown in table 15. (Glaize 2013)

Table 15: *Roles of the electrodes during charge and discharge (Glaize 2013)*

	Charge	*Discharge*
Positive Electrode	Anode	Cathode
Negative Electrode	Cathode	Anode

6.1.2 Gibb's free energy and standard potential

How much electrical energy can be released during the redox reaction and how much energy can be stored inside the battery? The maximum amount of energy corresponds to change of Gibb's free energy ΔG during the reaction. Gibb's free energy can be shown through equation:

$$\Delta G = \Delta H - T\Delta S, \tag{5}$$

where ΔH is the enthalpy of the reaction and it stands for the energy absorbed or released during the reaction. It provides the information how much chemical energy could be transformed to heat with 100 % efficiency. Entropy of the reaction is shown with $\Delta \boldsymbol{S}$ and it shows the reversible energy loss or gain with the reaction. T is temperature during the reaction in K. (Kiehne 2003) Change of Gibb's free energy can be said

$$\Delta G = QE, \tag{6}$$

where Q is a charge of the battery and E is the electric potential. Other way to describe the charge is

$$Q = nF, \tag{7}$$

where n is the amount of moles of electrons transferred in reaction and F is the Faraday constant. Faraday constant is the charge of electrons per mole (96 485 C/mol). When the previous equations are put together change of Gibb's free energy is

$$\Delta G = -nFE. \tag{8}$$

Minus sign in the equation comes from the fact that the redox reaction is spontaneous. When the reaction is spontaneous, change of Gibb's free energy is negative and electric potential is positive. When the reaction happens in standard conditions, which means concentration of 1 mol/l, pressure of 1 atm and temperature of 25 °C (LibreText 2020), equation changes to

$$\Delta G^{\circ} = -nFE^{\circ}, \tag{9}$$

where ΔG° is change of Gibb's free energy in standard conditions and E° describes the standard potential of the battery. (Park 2012)

6.1.3 Voltage and polarization

Voltage, which can be also called electromotive force, of the battery changes its value depending on conditions for example temperature and pressure. Therefore, standard potential is useful, so base value for the voltage can be set. Standard potential is measured under the standard conditions. Voltage of the battery is a potential difference between two electrodes. When there is not any current flow, the battery is in the balance state. In this state battery can supply the amount of energy of the Gibb's free energy. But during the battery discharge there is current flowing, and voltage is below the open circuit voltage, so maximum energy cannot be supplied. Open circuit voltage means the voltage difference between electrodes when there is not external load. Difference between operation voltage and open circuit voltage is due to polarization. (Park 2012) Voltage does not stay constant during the practical situation of discharge or charge. This can be seen from the figure 20.

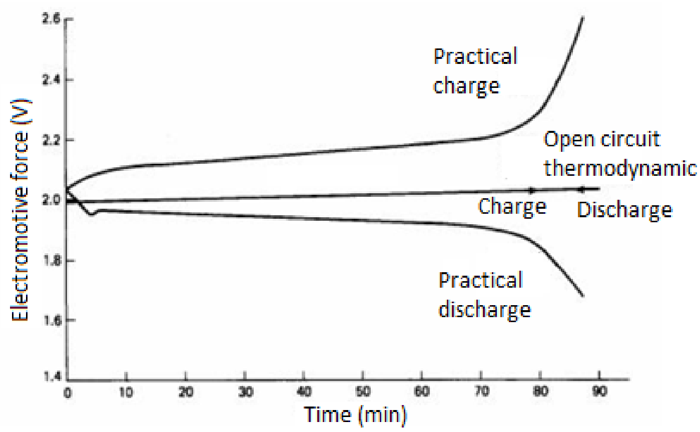


Figure 20: Practical and thermodynamic discharge and charge of the battery (Cropmton et al. 2000)

Voltage stays in the same level with the open circuit thermodynamic charge but in practical situations it decreases during the discharge and increases during the charge.

Polarization causes the variation of the voltage during charge and discharge. Polarization can be divided in two parts, overvoltage and ohmic voltage drop. Overvoltage happens because of the chemical reactions happening inside the cell that needs to keep up with the current flow. Electrons need to be guided into the right direction and reacting material needs to be transferred to the surface of the electrodes or carry away from it. Ohmic voltage drop is also caused by the current flow. Current flow through the conducting parts of the cell such as electrodes and electrolyte are the reason for ohmic voltage drop. Both parts of polarization cause irreversible losses which are generating heat. (Kiehne 2003)

6.1.4 Capacity, energy content and energy density

Capacity tells the amount of ampere hours (Ah) it is possible to discharge out of the battery or charge into the battery. General way to define capacity is

$$C_{Ah} = \int_0^t I(t)dt, \qquad (10)$$

where C_{Ah} is capacity in ampere hours, *I* is discharge current and *t* is the amount of time used for the discharge. Design of the battery is not the only thing that affects the capacity of the battery. (Kiehne 2003) One factor is the end-of-discharge voltage which means that if discharging the battery continues beyond a certain level of voltage that will damage the battery. With a lower end-of-discharge voltage level the capacity of the battery can be higher. (Barsukov et al. 2013)

Another factor is the discharge current. If the battery is discharged more quickly with higher discharge current, the capacity of the battery is decreased. This happens because the chemical reaction inside the battery does not have enough time to happen properly.

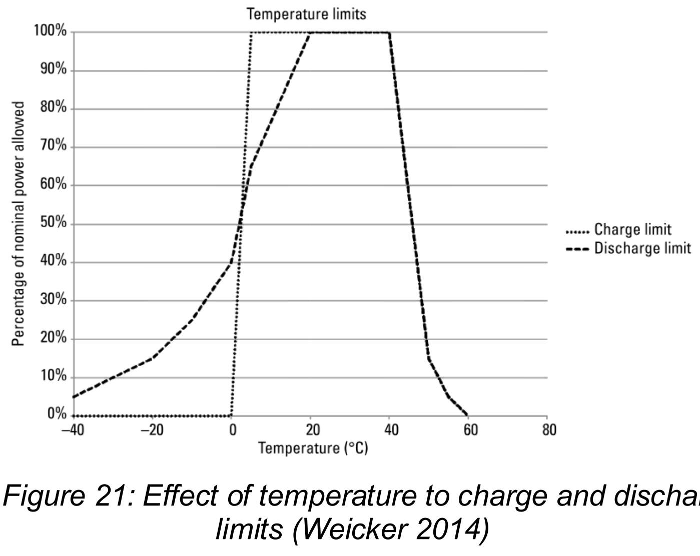


Figure 21: Effect of temperature to charge and discharge limits (Weicker 2014)

Third factor is temperature during the charge or discharge and battery manufacturers usually give a temperature range where the battery should be used. (Weicker 2014) If the temperature is over or under these limits qualities of the battery can be different. Example how temperature can affect the function of the battery is shown in the figure 21.

Depth of discharge (DOD) is a way to show how much electrical energy is already taken out of the battery. This is done by comparing extracted energy to capacity of the battery. DOD can be shown with equation

$$DOD = \frac{\int_0^t i(t)dt}{capacity}, \tag{11}$$

where *i* is the discharge current. This gives percentage value for the depth of discharge. Similar way state of charge (SOC) tells how much electrical energy there is left in the battery. SOC can be shown with equation

$$SOC = \frac{capacity - \int_0^t i(t)dt}{capacity}, \tag{12}$$

where *i* is the discharge current. SOC is also shown with percentage value. Connection between DOD and SOC is shown in the equation

$SOC = 1 - DOD$. (Glaize 2013) (13)

Sometimes with the capacity ampere hour value is not the most informative way because of the use of the battery. For example, the weight or the volume of the battery can be a crucial value. In these situations, capacity can be said with respect to weight (Ah/kg) or volume (Ah/l) (Park 2012).

Energy content tells how much energy (Wh) can be taken out from the battery or stored into the battery. Energy can be said

$$E = \int_0^t U(t)I(t)dt, \tag{14}$$

where *U* is the voltage of the battery, *I* is the discharge current and *t* is discharge period. (Kiehne 2003)

Also, energy density gives the energy value with respect to something else. With the gravimetric energy density energy is given per mass unit for example Wh/kg. Volumetric energy gives the amount of energy per volume unit such as Wh/l or Wh/cm^3. Same way as with the capacity it depends on the situation, what is the most informative way to say the energy density. With applications where you must move the battery during the operation weight is more important but on the other hand stationary energy storage systems weight usually isn't the problem but there can be limited amount of space where the storage should fit which gives restrictions for the volume. (Glaize 2013)

6.1.5 Cycle life

Battery can be charged and discharged a certain number of times before its capacity is reduced significantly. Cycle life describes how many of these charge/discharge cycles can be done for certain batteries. Cycle life depends on the battery type and how it has been used during its lifetime. (Park 2012)

The state of health (SOH) gives an estimation how the secondary battery has been aging and how long it is still usable for its function. SOH can be calculated with the equation

$$SOH = \frac{Q}{C}, \tag{15}$$

where *Q* is the total charge extracted during the discharge and *C* is the nominal capacity. SOH is usually shown as percentage value. One factor that affects the SOH during the lifetime of battery is operation temperature. Figure 22 shows how SOH of lithium-ion batteries changes with two different temperatures and discharge currents compared to the number of cycles. When the discharge current is 1C the total battery capacity is discharged for one hour.

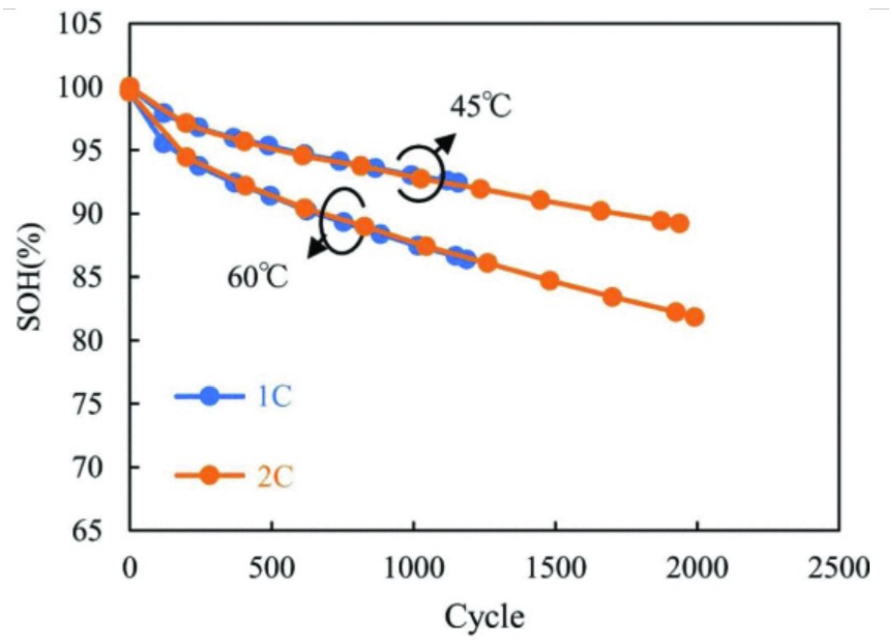


Figure 22: Value of the SOH with different temperature and discharge currents compared to number of cycles (Miftahullatif et al. 2019)

With these two discharge currents there is not much difference how they affect the SOH of the battery. On the other hand, with higher 60 °C SOH drops significantly lower with much fewer charge/discharge cycles compared to 40 °C.

Alongside with the operation temperature how charging and discharging is done affects the aging of the battery. Figure 23 is showing how different DOD affects the capacity of the lithium-ion battery compared to the number of charge/discharge cycles. Operation temperature is 25 °C and discharge current is 1 C.

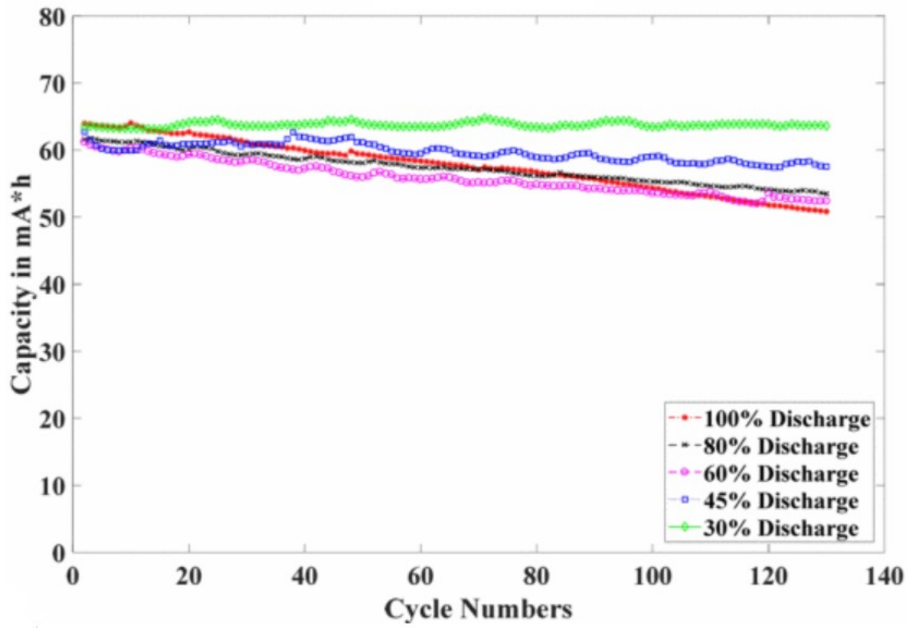


Figure 23: Effect of DOD to the capacity of the lithium-ion battery compared to number of cycles (Lall et al. 2019)

Depth of discharge affects considerably the capacity of the battery already during little bit 130 charge/discharge cycles. With 30 % DOD the capacity remains close to the same during the cycles. On the other hand, when the battery is discharged all the way from full capacity to empty, the change of capacity during cycles is significant. Capacity of the battery drops to about 80 % what it was before the cycles.

6.2 Power to gas

Power to gas (PtG) is a way to store electrical energy in chemical form. Surplus electrical energy that is produced by renewables is used to produce hydrogen through electrolysis. Principle of the PtG-concept is shown in the figure 24 from power generation to applications. In 2018 51.9 % of the produced hydrogen was used by industry especially for refining and 42.5 % for ammonia synthesis. Almost all this hydrogen is not produced through electrolysis. Instead, the source for hydrogen is either natural gas or coal because these two are clearly cheaper compared to hydrogen produced by renewable energy. Today price for hydrogen produced with renewables is 3.0-7.5 USD/kg when it is 0.9-3.2 USD/kg for natural gas. (IEA 2019)

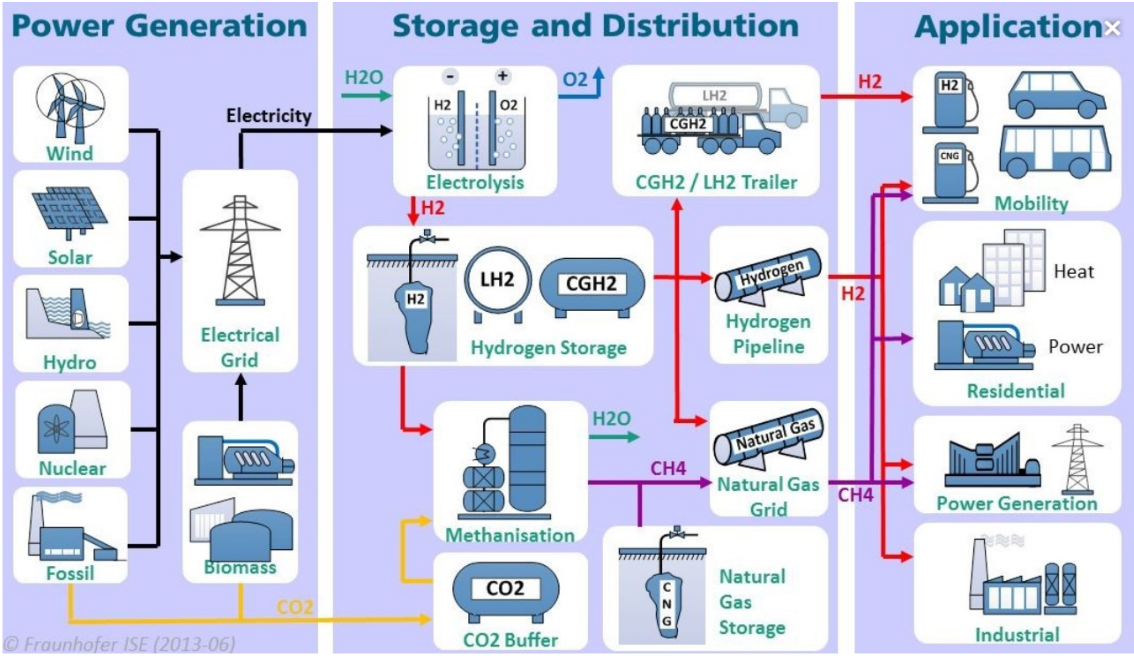


Figure 24: Principle of the power to gas –concept (Fraunhofer 2020c)

As shown in the figure hydrogen can be used in many ways after it has been stored. Hydrogen can be distributed by its own network or transported with trucks or even injected to natural gas networks. Through the methanation process hydrogen can be used to produce methane which can be also added to the natural gas network. Today produced hydrogen is mostly used by industry but there are many other applications where it can be used in the future. Hydrogen could be a notable option for transport, but this needs not only hydrogen price but also price of fuel cells to be competitive. This chapter concentrates on methods used during the storage and applications phases.

6.2.1 Electrolysis

Separating hydrogen from the water happens through electrolysis. Basic reaction for electrolysis is

$$2\,H_2O + energy \rightarrow 2\,H_2 + O_2. \tag{16}$$

Energy needed for the reaction to happen consists of both electrical and thermal energy. Amount of energy is 237.2 kJ/mol electrical energy and 48.6 kJ/mol thermal energy. Minimum voltage for reaction to happen can be calculated through Gibb's free energy. Gibb's free energy is calculated with equation 5. With temperature of 298 K (25°C) and pressure of 1 bar

$\Delta G =$ 285.84 kJ/mol – (298 K x 0.163 kJ/mol)

$$\Delta G = 237.26.$$

Reversible voltage for splitting water can be calculated through equation XX:

$$E_{cell} = -\frac{\Delta G}{nF} \tag{17}$$

$$E_{cell} = -1.227\ V,$$

where *F* is Faraday's constant and *n* is number of electrons. For producing one hydrogen molecule two electrons is needed. For this voltage to be high enough for the reaction all the components need to be in gaseous form. With conventional electrolyser temperature stays below 80°C and then reaction needs more energy to happen. This tells the thermoneutral voltage for the reaction which is 1.48 V. If the voltage is below reversible voltage there is no hydrogen production, between reversible and thermoneutral voltage reaction is endothermic and above thermoneutral voltage exothermic. (Boudellal 2018)

Electrolysers have their own efficiency during the hydrogen production and it can be calculated with the equation 18:

$$\eta = \frac{moles\ of\ hydrogen\ produced\ x\ HHV_{H_2}}{IVt}, \tag{18}$$

where *HHV* is higher heating value of hydrogen, *I* is the cell current, *V* is the voltage and *t* is the time of production. (Letcher 2016) How cell voltage affects the cell efficiency is shown in the figure 25.

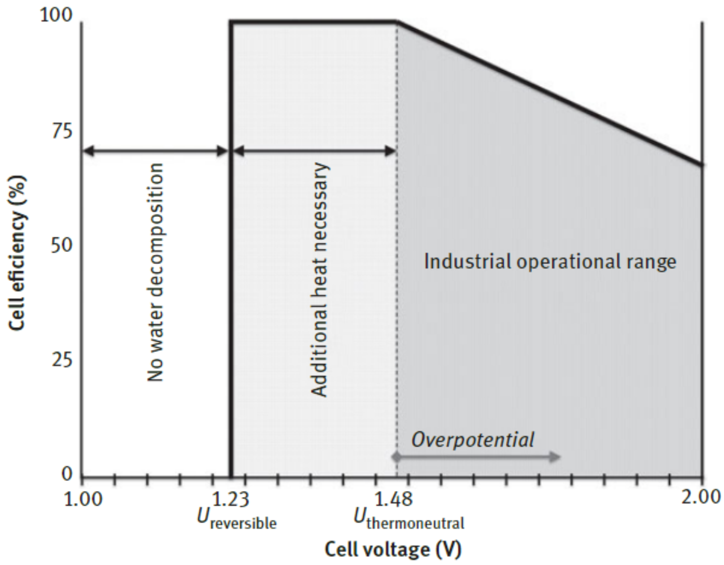


Figure 25: Cell voltage compared to cell efficiency (Boudellal 2018)

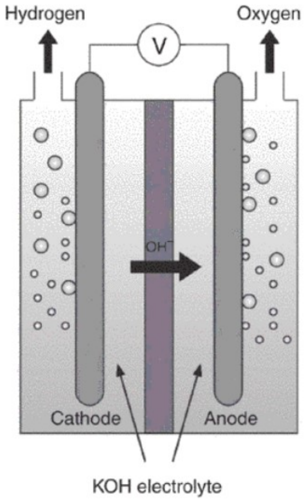
Up to reversible voltage, there is no hydrogen production, and the efficiency stays in zero. When the voltage exceeds the reversible limit, but stays under the thermoneutral voltage, there is a need for adding heat into the system and the efficiency has its highest point. When the voltage is exactly on the thermoneutral level, there is neither need for additional heat nor there is heat production. After the thermoneutral limit the reaction produces additional heat and the efficiency starts to decrease, but the operation happens in this area past the thermoneutral limit.

Water is an essential part of the hydrogen production, so it is interesting how much water is needed during the hydrogen production. The amount of water compared to the volume of hydrogen is shown in table 16.

Table 16: *Volume of water compared to produced volume of hydrogen (Boudellal 2018)*

Volume of hydrogen in 1 atm	*Volume of water*
1 mol	18 cm^3
100 m^3	80 400 l

Electrolysis can be done with few different methods: alkaline electrolysis, proton exchange membrane (PEM) and solid oxide electrolysis (SOE). Alkaline electrolyser and reactions in cathode and anode are shown in the figure 26.



Cathode Reaction

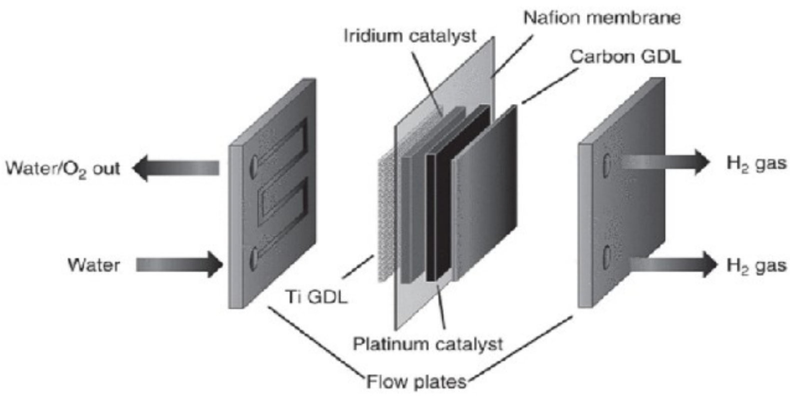
$$H_2O_{(l)} + 2e^- \longrightarrow H_{2(g)} + 2OH^-_{(aq)}$$

Anode Reaction

$$2OH^-_{(aq)} \longrightarrow 2H_2O_{(l)} + {}^1/_2O_{2(g)} + 2e^-$$

Figure 26: Alkaline electrolyzer and anode and cathode reactions (Letcher 2016)

Alkaline is the oldest of the electrolysis methods and potassium hydroxide is usually used as electrolyte. Nickel or some compound of nickel is usually used as material of the electrodes. The other option for the electrolysis is PEM which has a different kind of structure compared to alkaline. PEM electrolyser and reactions happening inside are shown in the figure 27.



Cathode Reaction

$$2H^+_{(aq)} + 2e^- \longrightarrow H_{2(g)}$$

Anode Reaction

$$H_2O_{(l)} \longrightarrow {}^1/_2O_{2(g)} + 2H^+_{(aq)} + 2e^-$$

Figure 27: PEM electrolyzer and anode and cathode reactions (Letcher 2016)

With much a newer and more complicated structure PEM is still a more expensive option compared to alkaline. On the other hand, PEM has also higher potential considering the performance. (Boudellal 2018) In table 17 are shown the characteristics of alkaline, PEM and SOE which is still in the research and development phase.

Table 17: *Characteristics of the electrolyzers (El-Shafie et al. 2019)*

	Alkaline	***PEM***	***SOE***
Technology maturity	State of art	Demonstra-tion	R&D
Cell temperature (°C)	60-80	50-80	900-1000
Current density (A/cm^2)	0.2-0.4	0.6-2.0	0.3-1.0
Cell pressure (bar)	<30	<30	<30
Cell voltage (V)	1.8-2.4	1.8-2.2	0.95-1.3
Power density (W/cm^2)	< 1.0	< 4.4	-
Voltage efficiency (%)	62-82	67-82	81-86
Specific system energy consumption (kWh/Nm^2)	4.5-7.0	4.5-7.5	2.5-3.5
Partial load change (%)	20-40	0-10	-
Cell area (m^2)	<4	<300	-
Hydrogen production (Nm^2/h)	<760	<30	-
Stack lifetime (h)	<90 000	<20 000	<40 000
System lifetime (a)	20-30	10-20	-
Hydrogen purity (%)	>99.8	>99.999	-
Cold start-up time (min)	15	<15	>60

How much energy does hydrogen production through electrolysis need? For producing 1 kg of hydrogen energy consumption is about 55 kWh and for a source material there is need for 10 l of demineralized water (Thomas 2018).

6.2.2 Hydrogen storage

After hydrogen has been produced by electrolysis there are a few ways how it can be stored. First option is compressed hydrogen storage which is the most common way to store hydrogen. Reason for compressing the hydrogen during the storing is the low density of hydrogen. For 1 kg of hydrogen, it will take 12.15 m^3 in normal temperature and normal pressure. Amount of gasoline that would provide the same amount of energy needs only 0.0038 m^3. Because of this gaseous hydrogen is stored in 200—800 bar pressure, so the volumetric density can be increased. Pressurising hydrogen increases the costs of the storage method and brings along possible safety issues. (Sankir et al. 2018, Carriveau et al. 2016)

Another option is to store hydrogen in liquid form. This way the volumetric density can be increased. Because of the low boiling point of hydrogen, it needs to be stored at –252 °C (21 K) in a cryogenic container at ambient pressure. Storing hydrogen in liquid form requires a lot of energy to maintain the optimal conditions and this decreases cost-effectiveness of the solution. (Sankir et al. 2018, Carriveau et al. 2016)

Third option is to use solid storage of hydrogen. This is possible when hydrogen combines with ally creating metal hydrides for example MgH_2 Mg_2NiH_4. Hydrogen locates itself at the surface of the alloy and then takes its place in the structure of the crystal lattice. Later hydrogen can be taken out of the metal hydride by heating it. In this type of hydrogen storage, the biggest problem can be the mass of the system because the hydrogen in the system stands for under 10 % of the whole system mass depending on which alloy is used. Figure 28 shows the difference between these options considering the mass and the volume of the system which is storing 3 kg of hydrogen. (Boudellal 2018)

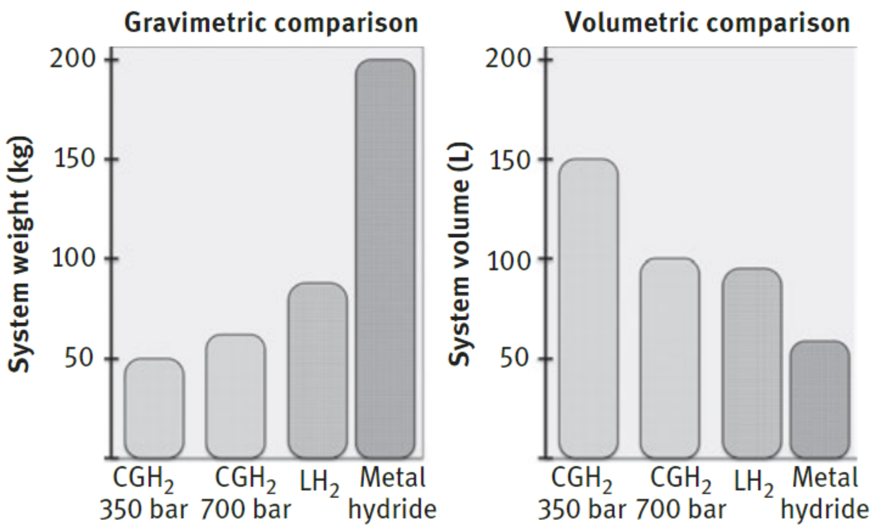


Figure 28: Gravimetric and volumetric comparison of storage capacity for 3 kg of hydrogen (Boudellal 2018)

6.2.3 Methanation

After production hydrogen can be used to create methane. During the methanation process hydrogen is combined with carbon dioxide. Reaction for methanation is

$$CO_2 + 4\,H_2 \rightarrow CH_4 + H_2O. \tag{19}$$

Methanation reaction is exothermic and under standard conditions ΔH = -164.6 kJ/mol. (Boudellal 2018) The structure for the methanation process is shown in the figure 29.

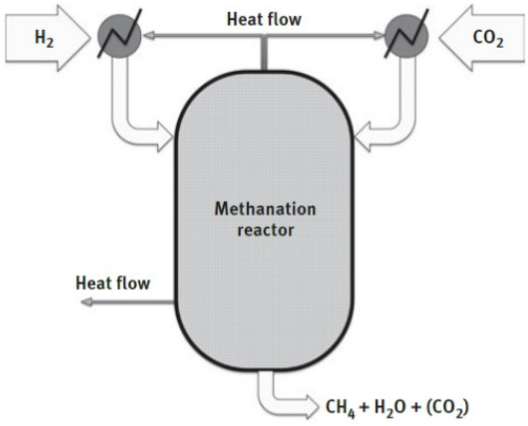


Figure 29: Methanation process (Boudellal 2018)

Reaction products in the picture 29 are showing carbon dioxide. Amount of carbon dioxide depends on the pressure and temperature. If methane content needs to be 90 % or 95 %, the conversation range of carbon dioxide must be close to 98 % and 99 % respectively. (Carriveau et al. 2016) Conditions and characteristics of the methanation process are shown in the table 18.

Table 18: *Characteristics of the methanation (Letcher 2016)*

Sector	*Key figures*
Operating pressure (10^5 Pa)	6-8
Operating temperature (°C)	180-350
Efficiency (%)	70-85

6.2.4 Fuel cell

After the production of hydrogen there might be a situation where it is not sensible to use hydrogen for other applications and it is needed to convert back to electricity. This can be done by using fuel cells. Fuel cell has a similar structure to electrolysers which is shown in the figure 30.

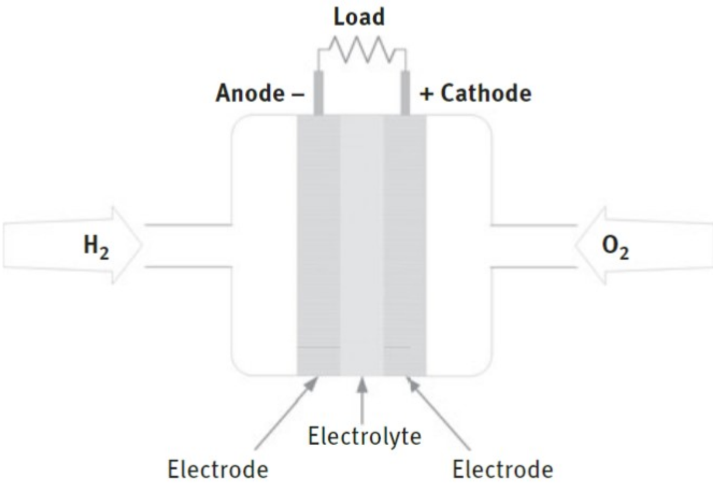


Figure 30: Structure of the fuel cell (Boudellal 2018)

Electricity is produced through electrochemical reactions like in batteries but for fuel cell source material for reaction are fed from outside. For batteries they are already inside of the battery. During the electricity production there is a hydrogen combustion reaction happening inside the fuel cell. Reaction for the proton exchange membrane (PEMFC) and phosphoric acid (PAFC) fuel cells can be shown in two different electrochemical reactions.

$$H_2 \rightarrow 2H^+ + 2e^- \tag{20}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{21}$$

First reaction is happening at the anode and the second one in the cathode. (Cha et al. 2016) These are the basic reactions in fuel cells, and they change depending on the type of fuel cell. There are different types of fuel cells which have differences in used materials, type of fuel and operation characteristics. They can be used for different applications based on their properties. In table 19 there are shown characteristics for five different fuel cell types.

Table 19: *Characteristics of the different types of fuel cells (Gencell 2017, DOE 2015, Vaghari et al. 2013)*

Type	*Solid Oxide Fuel Cell (SOFC)*	*Molten Carbonate Fuel Cell (MCFC)*	*Alkaline Fuel Cells (AFC)*	*Phosphoric Acid Fuel Cell (PAFC)*	*Proton Exchange Membrane Fuel Cell (PEMFC)*
Fuel	Hydrogen Methanol Biogas Ethanol Natural gas	Hydrogen Methanol Biogas Ethanol Natural gas	Hydrogen	Hydrogen Methanol	Hydrogen
Power (kW)	0.01-2000	10-2000	0.5-200	100-400	0.12-5
Temperature	700-1000	630-650	50-200	190-210	50-200
Electrical Efficiency (%)	50-60	50	60-70	40-50	30-60
Efficiency with CHP (%)	80-85	80	80	80	-
Start-up time (min)	60	10	< 1	-	< 1

7. ENERGY STORAGE IN NYKARLEBY

Idea for the energy storage system is that the storage would operate alongside the Björkbacken wind farm. It is estimated that the 26 turbines with 5.6 MW nominal power would have the gross production of 557.90 GWh per year. After all the losses have been taken into account the most likely yearly energy production would be 476.28 GWh. (Energiequelle 2020c)

For energy storage it is important to know how the yearly energy production is spread over the year. Production data from Jeppo 1-2 wind power plant from the year 2018 has been used to estimate this information. Data gives average production for every 10 minutes and from that it is calculated average energy production for every hour over the year. Jeppo 1-2 has two turbines and average production of those has been used to calculate the hourly production of Björkbacken. This average production is multiplied by 26 to match the number of wind turbines in Björkbacken, which means that in the calculations all the turbines would have the same production. Turbines in Jeppo 1-2 are also smaller, so hourly production estimations are scaled up to match the total estimated yearly production of Björkbacken. Scaling up has been done during the hours when there has been production. Based on the production data during the year there would be 780 hours with no production.

7.1 Battery storage

For a wind farm, it is normal to have a PPA for a longer period. With Björkbacken it is for 10 years with a price of 3.1 c/kWh. To fulfil the PPA plant should produce 70 % of the estimated yearly production. If production is less than 70 % rest of the energy must be bought from the electricity market and when production is more than 70 %, the rest can be sold to the market. Goal for the plant is to help fulfil the PPA and reduce the need to buy electricity from the market.

It is assumed that Björkbacken would start to operate in 2024 and the PPA deal would be active 2024-2033. Table 20 shows estimated electricity prices for that period and these prices are used to calculate incomes for the sold electricity and costs when electricity must be bought from the market. Prices are the same as in the feasibility evaluation with solar power.

Table 20: *Estimated electricity prices (Energiequelle 2020c)*

Year	*Electricity price (c/kWh)*
2024	3.99
2025	4.36
2026	4.54
2027	4.86
2028	5.20
2029	5.49
2030	5.78
2031	5.88
2032	5.87
2033	5.89
Average	**5.19**

7.1.1 Wind power without the storage

Production goal for the Björkbacken with 70 % PPA is 333.4 GWh per year, which means 38.1 MWh for every hour. When there is a 24-hour period when there is no production, it is possible to inform the parties of the PPA that there is no production. When this is done, then there is no obligation to fulfil the PPA for that 24-hour period. With Björkbacken 168 hours out of the 780 with no production are part of this kind of 24 hours period.

Table 21: *PPA, surplus and deficit hours for one year and average amount of energy*

	Number of hours
For PPA	7980 (32.1 MWh)
To market	5350 (22.3 MWh)
From market	**3242 (5.3 MWh)**

Table 21 shows the number of hours for a one year when there is some energy delivery for the PPA, surplus energy after fulfilling the PPA and when there is a need to buy more electricity from the market. It also shows the hourly average amount of electricity for categories. For 91.1 % of the hours there is some delivery for the PPA, and the average energy amount fulfils 84.4 % of the electricity need of the PPA. From a total 8760 hours in a year, for 61.1 % there is a surplus after fulfilling the PPA and for a 37.0 % there is a deficit.

Table 22: *Key figures for wind power plant without the storage with PPA*

	Key Figures (€)
PPA incomes	87,067,600
Market incomes	101,266,113
Market costs	23,927,622
Total	**164,406,092**

Table 22 shows financial figures for the power plant for the 10-year period when the PPA is active. As can be seen from the table, market incomes are larger than the incomes from the PPA, which is explained by higher price for electricity outside of the PPA and there are a lot of hours when the PPA is fulfilled easily.

7.1.2 Wind power with the storage

With the storage, the situation is different compared to the power plant without the storage. When there is surplus energy after fulfilling the PPA, some of it can be stored and used when the production is lower. This way it is possible to decrease the amount of energy that must be bought from the market to fulfil the PPA.

Tables 23 and 24 show the number of hours for one year when there is some energy for PPA, surplus hours and hours when there is a need to buy more energy. Number in brackets shows in MWh what is the average amount of energy per hour, which is sold to the market or brought from it. There is also the number of hours, when there is a charge in the storage and the average amount of charge in the storage in MWh. Table 23 shows the numbers for 70 % PPA and table 24 for 75 % PPA. For the storage it is taken account that there would be 20 % loss during the charge-discharge cycle and DOD can be anything between 0-100 %.

Table 23: *Key figures for wind power plant with the storage and 70 % PPA*

	Key figures		
Capacity (MWh)	10	20	50
For PPA (h)	7987 (32.4 MWh)	7998 (32.6 MWh)	8042 (33.2 MWh)
With Capacity (h)	5797 (6.2 MWh)	6059 (12.5 MWh)	6487 (32.1 MWh)
To market (h)	5015 (22.0 MWh)	4868 (21.7 MWh)	4613 (21.2 MWh)
From Market (h)	**2795 (5.0 MWh)**	**2533 (4.7 MWh)**	**2105 (4.2 MWh)**

With the 70 % PPA there is not much difference for the number of hours or the average energy when looking at the "For PPA"-row, which is understandable, because the production of the plant and the need for PPA stays the same, but capacity of the storage slightly increases the numbers. Surplus energy to the market decreases, when the storage capacity goes up, because the extra energy is now stored, when it is possible. Biggest difference comes with the hours when there is a need to buy energy from the market. The drop with the number of hours is from 447 to 1137 depending on the capacity of the storage. So, the percentage for the deficit hours decreases from 37.0 % to the value 24.0-31.9 % and the average value for one hour is also slightly smaller. There is some charge inside the storage for at least 66.2 % of the hours during the year and with 50 MWh storage the percentage is 74.1 %. So, clearly for most of the year storage is in good use, but the average charge stays between 16.3 % and 84.3 % of the requirement for the PPA depending on the capacity. This means that usually the storage cannot cover the PPA requirements for hours with no production, but it can certainly help when the production does not quite reach the requirements.

Table 24: *Key figures for wind power plant with the storage and 75 % PPA*

	Key figures		
Capacity (MWh)	10	20	50
For PPA (h)	7985 (34.0 MWh)	7992 (34.3 MWh)	8020 (34.8 MWh)
With Capacity (h)	5440 (5.8 MWh)	5689 (11.7 MWh)	6116 (30.0 MWh)
To market (h)	4747 (20.4 MWh)	4579 (20.1 MWh)	4322 (19.5 MWh)
From Market (h)	**3152 (6.0 MWh)**	**2903 (5.7 MWh)**	**2476 (5.2 MWh)**

With the 75 % PPA, hours when there is some energy for PPA are between the two previous cases. There is least surplus energy because the hourly need for PPA is higher, 357.2 GWh yearly and 40.78 MWh for every hour. Need for energy from the market is higher than with 70 % PPA but it is still less than without the storage. The drop with the number of hours, when there is a need to buy electricity, is from 90 to 766 when comparing the situation when there is no storage. The percentage for the deficit hours is 28.3-36.0 % but the average value for one hour is slightly higher than without the storage. There is some charge inside the storage for at least 62.1 % of the hours during the year and with 50 MWh storage the percentage is 70.0 %. The average charge stays between 14.2 % and 73.6 % of the requirement for the 75 % PPA and the percentage depends on the capacity of the storage.

Table 24 shows the key figures for different PPA and storage capacity. PPA is active for the same 10 years than without the storage and electricity prices are the same. There is added costs for storage system, and it is 500,000 €/MWh (Energiequelle 2020c).

Table 25: *Key figures for the wind power plant with the storage and PPA*

			Key Figures (€)			
PPA (%)	70	70	70	75	75	75
Capacity (MWh)	10	20	50	10	20	50
PPA incomes	87,929,004	88,590,316	90,060,937	92,324,110	93,020,152	94,575,176
Market incomes	99,846,114	98,784,009	96,338,712	92,486,723	91,353,429	88,765,727
Market costs	22,486,576	21,381,489	18,936,840	27,247,082	26,082,672	23,492,408
Storage invest-ment	5,000,000	10,000,000	25,000,000	5,000,000	10,000,000	25,000,000
Total	**160,288,542**	**155,992,836**	**142,462,809**	**152,563,752**	**148,290,910**	**134,848,495**

Market incomes for 70 % PPA are bigger than PPA incomes, like it is without the storage. The situation turns around with 75 % PPA, when the capacity is 20 or 50 MWh. With 75 % PPA total profit is easier to estimate because a bigger share of the energy is sold with the price of the PPA and it is not dependent on what the market price is at a specific hour. Market costs without the storage is 23,927,622 €, so it is higher than equivalent costs with all 70 % PPA with all storage capacities and with 50 MWh storage capacity with 75 % PPA. Although, the difference is not enough to cover the investment costs of the storage system. The total profit without the storage is 164,406,092 €, which means that the storage system is not financially feasible with these electricity prices.

Table 25 shows the same key figures as the previous table but the price of the PPA is different. Table shows how the price should increase to make the storage system financially feasible.

Table 26: *Key figures for the wind power plant with different PPA prices*

	Key Figures (€)					
PPA (%)	70	70	70	75	75	75
Capacity (MWh)	10	20	50	10	20	50
PPA price (c/kWh)	3.3	3.4	3.9	3.5	3.5	4.1
PPA incomes	93,601,843	97,163,572	113,302,469	104,236,899	111,024,052	125,083,297
Market incomes	99,846,114	98,784,009	96,338,712	92,486,723	91,353,429	88,765,727
Market costs	22,486,576	21,381,489	18,936,840	27,247,082	26,082,672	23,492,408
Storage invest-ment	5,000,000	10,000,000	25,000,000	5,000,000	10,000,000	25,000,000
Total	**165,961,381**	**164,566,092**	**165,704,342**	**164,476,540**	**166,294,810**	**165,356,616**

Previous calculations have been done with a 3.1 c/kWh price for the PPA. As it can be seen, the smallest change is needed for 10 MWh storage with 70 % PPA with the increase of 0.2 c/kWh. Also, with 20 MWh storage with 70 % PPA and both 10 MWh and 20 MWh capacity with 75 % PPA the increase is 0.4 c/kWh or less. Highest increase of the price is needed for the biggest 50 MWh storage systems. Even with the increase of the PPA price, market incomes affect a lot to the total profit. In these calculations market incomes and market costs have been calculated with one price for the whole year, when in the real situation price could vary a lot during the year. Moments when the surplus is sold to market and moments when more energy is needed from the market have a great impact for the total profit of a wind power plant with or without the energy storage.

Now the concentration has been on the first ten years of operation of the wind power plant when the PPA is active and all the numbers are from that period. Operating time for a wind power plant is 30 years and the storage is also useful after the PPA is finished. Electricity grid can benefit from storage. For example, it can be used to help to control frequency of the grid by providing more power to the grid or more consumption when the storage is charged. For the owner, the storage can be also financially beneficial because the stored energy does not need to be sold right away. Instead, it is possible to wait a moment to get the best price for the sold electricity.

7.2 Power to gas -system

Another option for energy storage instead of the battery system is power to gas- system. Part of the electricity from the wind power is used to produce hydrogen. Like the battery system, power to gas -system would be combined with Björkbacken wind power plant. Total yearly production of Björkbacken would be 476.28 GWh and 20 % of that would be used for hydrogen production. Rest of the energy would be fed into the grid.

7.2.1 Hydrogen production

Total energy for hydrogen production is 95.26 GWh and it is divided for a year based on the data from Jeppo 1-2. For every hour 20 % of the produced energy is used for hydrogen production. Water is the most important material for hydrogen production. If normal drinking water is used for the production, there is a need for 18.7 kg of water per produced kilogram of hydrogen. Energy needed to produce 1 Nm^3 of hydrogen is 4.9 kWh. (H-TEC Systems 2020) When the density of hydrogen is 0.0899 kg/m^3, the needed energy per kilogram is 54,5 kWh. The maximum hourly energy for production is 22.9 MWh, which equates to 416.3 kg of hydrogen. The average hourly energy for production is

10.87 MWh and with that energy it is possible to produce 199.5 kg of hydrogen. Total produced hydrogen could be 1,747,812 kg every year. If ME 450/1400 from H-TEC is used for example this kind of production would need an electrolyser system of 22.4 MW (H-TEC Systems 2020). Table 26 shows what the investment costs have been for electrolysers and what is the estimation for the future.

Table 27: *Investment cost of different kind of electrolysers (European Commission 2015)*

Electrolyser type	*Alkaline*		*PEM*		*SOE*
Year	2013	2030	2013	2030	2030
Investment cost (€/kW)	650-1200	370-800	1860-2320	250-1270	625

As it can be seen from the table prices are estimated to drop distinctly when comparing year 2013 to year 2030. With prices of 2030, 22.4 MW alkaline system would cost 8.3-18.0 M€ and with PEM system 5.6-28.4 M€. SOE is newer technology and with its estimation the 22.4 MW system would cost 14 M€ in 2030. Yearly operation costs are estimated to be 2-5 % of the investment costs with all the electrolyser types (European Commission 2015).

7.2.2 Use of hydrogen

Hydrogen can be transformed back to electricity by using a fuel cell, but the efficiency for this is quite low if it is compared to the situation when electricity is stored in batteries. So electricity is better to store in batteries but if the hydrogen is produced it is better to use some other way. One option is located right next to Björkbacken wind power plant. There is a company called Jeppo biogas, which is producing biogas from cow and pig manure. In their process there is a surplus of carbon dioxide (CO_2). This could be used together with hydrogen and create methane (CH_4) through the methanation reaction.

When the biogas plant is working with full capacity, the surplus CO_2 can be 300 Nm^3/h. (Stenvall 2020) When the density of CO_2 is 1.98 kg/m^3, it means 594 kg of CO_2 per hour and 5,203,440 kg per year. If all the CO_2 can be used in methanation, then the need for hydrogen is 957,432 kg per year and 109.3 kg per hour. (Baier et al. 2018) Combining these two it could be possible to produce 1,873,238 kg of CH_4 and 4,246,003 kg of water (H_2O) as a by-product in a year.

Jeppo biogas would be the primary user of the hydrogen and they get 109.3 kg every hour whenever it is possible, and the rest of the hydrogen would be stored. Then, the biogas plant would get their maximum need for hydrogen for 95.1 % of the hours during the year and the average delivery of hydrogen would be 106.1 kg per hour. In this case, the average amount of hydrogen in storage would be 3156 kg and the maximum amount would be 9686 kg if hydrogen for the biogas plant can be delivered straight away to the power plant. Hydrogen needs to be pressurized for the storage and it takes 1.6 kWh/kg to pressurise the hydrogen to 700 bar. This consumes a little amount of energy that is reserved for the hydrogen production.

Hydrogen can be also used elsewhere, which would decrease the capacity of the storage unit. One option would be to use a fuel for passenger vehicles. One refill for the car would take 5.6 kilograms of hydrogen (Huyndai 2014). Table 27 shows how different numbers of refills for one hour affect hydrogen delivery for Jeppo Biogas and usage of storage.

***Table 28**: Status of hydrogen delivery and storage with different number of refills*

Number of refills in hour (pcs)	*Full delivery for biogas (%)*	*Average delivery for biogas (kg)*	*Hours with hydrogen in Storage (%)*	*Average hydrogen in storage (kg)*	*Maximum hydrogen in storage (kg)*
10	84.7	101.3	76.9	1758.1	7722.1
20	78.3	98.8	57.0	875.1	5832.4
30	75.2	97.6	40.0	384.9	4025.2
40	74.2	97.3	25.7	115.1	2238.3
50	74.1	97.3	10.1	9.6	475.8

Even though the share of full delivery hours drops about 10 %, it does not have much effect on average delivery. Average delivery drops 4 kg from 10 refills to 50 refills per hour, but still with 50 refills the average delivery is 89.0 % of the maximum need. Change in the number of refills makes more difference for the status of the storage unit. Share of hours with hydrogen storage drops to 10 % with the 50 refills and then the average amount of hydrogen in storage is under 10 kilograms, which is not enough for two full refills. There is almost no buffer if the need for hydrogen suddenly increases. For fewer refills per hour the situation is better and there is a buffer for sudden needs. Even though the average amount of hydrogen might be quite small the maximum amount is clearly higher, which indicates the big differences for wind power production between hours. If the storage capacity is estimated based on the maximum amount of hydrogen in storage, it would be from 500 to 8000 kg. In volume this would mean that capacity is 15.5-200 m^3, when the density of hydrogen in 700 bar is about 40 kg/m^3 (Léon 2008). Investment costs for the storage in 2030 is estimated to be 75 €/m^3 of hydrogen (Gorrea et al. 2019). So, the investment costs would be 937.5-15000 €.

Today there is no use for hydrogen in traffic, which is understandable because there is no infrastructure for refuelling in Finland. Instead, most of the hydrogen is used for oil refining and biofuel production and only 1 % of hydrogen is produced by using water electrolysis. (Laurikko et al. 2020) In 2013 VTT made a plan for a hydrogen refuelling station, where 20 stations could cover the main roads for the whole Finland (Kauranen et al. 2013). One of them could be in Nykarleby. Same plan also gives estimation for the need of hydrogen for passenger cars in the future. Table 28 shows these yearly estimations with conservative and optimistic versions.

Table 29: *Estimation of the need of hydrogen in passenger cars (Kauranen et al. 2013)*

Year	*Conservative estimation (kg)*	*Optimistic estimation (kg)*
2030	12,500,000	23,900,000
2040	29,100,000	58,300,000
2050	58,400,000	116,800,000

Accuracy of the estimations depends on how technology and prices of hydrogen cars develop. Also, the refuelling network needs to be wide enough before large use of hydrogen in vehicles can be possible. This creates a problem of which ones should come first: hydrogen cars or hydrogen refuelling stations. There is potential for hydrogen production with wind power and with 20 % of the energy produced with Björkbacken could be produced 14.0 % share of the conservative estimation for the year 2030 if all of the produced hydrogen is used for vehicles. If the primary use of hydrogen is to deliver it to the Jeppo Biogas, then the amount of hydrogen for the vehicles covers 7.2 % of conservative estimation for the year 2030.

8. SUMMARY

Nykarleby has a long history with producing energy by using renewable energy due to the hydro power plant in the centre of the city. In the recent years, the variation in the used technologies has been widened with biogas and wind power stepping in the picture. In the next few years, the share of the wind power in energy production is significantly increasing with four new wind power plant projects. With these projects the size of the wind power plants can increase from 7 MW to 370 MW.

Solar power has a potential in Nykarleby, and the power plant could produce 947 kWh/kWp per year. Same number for Hanko is only 27 kWh/kWp per year higher, even if Hanko is the most southern city in Finland. For the solar power plant in Nykarleby there were two different business models under evaluation. In the model 1, one company would build the solar power plant and then would sell it to another company which would control the power plant for 30 years, when the plant is active and sells the produced electricity. For the builder company this model is not profitable with current PPA prices, market prices and investment costs. For the second company it is feasible and the payback time for the investment would be 18.8 years. To make model 1 profitable also for the builder company, it would need a 2.5 c/kWh increase in PPA price, 3 % increase in efficiency and 10 % decrease in module prices.

In the second model, one company would build the power plant and take care of it for the whole operation time and sell the produced electricity. In this case the power plant would be feasible and payback time for the investment would be 21.6 years. Solar power plant would also be a good solution, when the company could use the electricity on its own.

Usually, PPA for wind power plants states that the plant should produce 70 % of the estimated electricity production for every hour or the missing energy need to be bought from the market. Without the battery storage in Björkbacken wind power plant, based on the production estimation, 37.0 % of the hours there would be a need to buy more electricity from the market to fulfil the PPA. With the storage the percentage drops to 31.9 %, 29.0 % and 24.0 % with 10 MWh, 20 MWh and 50 MWH storage capacity, respectively. Financial benefits from the storage does not cover the investment costs of the storage with current PPA price. The smallest change would be with the 10 MWh storage capacity, which would need 0.2 c/kWh higher PPA price for the storage to be profitable.

Battery storage can be also used to increase the needed percentage of PPA from 70 % to 75 %, which increases the predictability of the incomes when more of the produced electricity is sold based on the PPA price. This solution can be feasible with 10 MWh or 20 MWh storage capacity if the PPA price is increased 0.4 c/kWh from the original situation.

Electricity from the Björkbacken could be used as a part of a power-to-gas system and produce hydrogen. One place where hydrogen could be used is the biogas plant of Jeppo Biogas, which is located right next to the Björkbacken wind power plant. It could be used as a part of the methanation process to produce methane. If 20 % of the estimated production of Björkbacken would be used to produce hydrogen, it would cover 95 % of the maximum need of Jeppo Biogas. Rest of the hydrogen could be used as fuel for hydrogen vehicles. Number of vehicles that could be refilled depends on the amount of hydrogen that is delivered to the biogas plant. Use of hydrogen in traffic also depends a on lot how popular hydrogen vehicles will become in the future and how the hydrogen refuelling network will develop in Finland.

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