Bachelor's project

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Lene T. B. Erichsen
Ingebjørg Slåtta
Mathea Lie Tærum

# An airports role in the transition to sustainable aviation with the implementation of electric planes

## Design of a resilient and sustainable local energy system at Åre Östersund airport

Bachelor's project in Renewable Energy Engineering
Supervisor: Håvard Karoliussen and Alejandro O. Barnett
May 2021

NTNU
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| **Report title:**<br>An airports role in the transition to sustainable aviation with the implementation of electric planes<br>**Report title Norwegian:**<br>Flyplassens rolle i luftfartens grønne skifte med introdusering av elektriske fly | **Project assigned:** 08.10.20<br>**Number of pages / appendices:** 116 / 8<br><br>**Submission deadline:** 20.05.21 |
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# Preface

This BSc thesis is written in collaboration between three students at the Norwegian University of Science and Technology in Trondheim. It is the final assignment in the bachelor program Renewable Energy Engineering at the Department of Energy and Process Engineering. It is written in the course TFNE3001 Bachelor Thesis Renewable Energy and is worth 20 credits. The BSc thesis is developed in collaboration with Tor Didrik Krog at Siemens AS.

The thesis analyses the implementation of charging of electric planes in current airport infrastructure. It has been inspiring to contribute in the early development phase in the electrification of the aviation sector.

We would like to thank our external supervisor, Nordic Head of Sales & Business Development in Siemens Tor Didrik Krog, for counselling, informative discussions, technical guidance and providing us with sources of information. Our greatest gratitude is also sent to our co-external supervisor, Tor Hennum, for helpful discussion, software guidance and constant support.

We would also like to thank our internal supervisors, associate professor II at NTNU and chief technology officer in Hystar Alejandro Oyarce Barnett and associate Professor at NTNU Håvard Karoliussen, for help, guidance and valuable feedback throughout the process.

Our appreciation is directed to contributors from main cooperating companies Siemens AS, Green Flyway, Swedavia AB, Jämtkraft AB and Northvolt AB for sharing valuable information and advice. Special thanks to Green Flyway and Swedavia for inviting us to a digital partner meeting and allowing us to join their webinar about *Fire safety in change due to electrification*. It would have been interesting and beneficial for the thesis to visit Åre Östersund Airport, but this was unfortunately not possible due to Covid-19.

Trondheim, 20.05.2021

Lene T.B. Erichsen — Ingebjørg Slåtta — Mathea Lie Tærum

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## Abstract

Aviation is crucial in both short- and long-distance mobility in the world today and provides important social benefits. An ongoing electrification and commercialization of aircrafts aims to reduce the large negative climate impacts. The electrification causes a large increase in power demand and challenges in grid capacity world wide. Green Flyway is a unique Nordic partnership between Norway and Sweden, and works as a test arena for electric aircrafts with a focus on developing sustainable infrastructure and promoting research. It is expected that the first commercial all-electric airplane, ES-19, will depart from the airport by 2026.

This bachelor thesis addresses the implementation of charging stations for electric airplanes in existing airport infrastructure while maintaining security of supply. The main objective is securing a sustainable energy- and charging system at Åre Östersund airport. The energy system was simulated in MATLAB and PSS DE®Siemens over a 20 year timeline. The simulation analyses three steps in the commercialization of the electrical aviation field. The first step is a test arena with small electric planes. Then electric planes as part of the public transport system as shuttle traffic. Lastly shuttle traffic in combination with the thought largest electric planes with longer range.

Results from MATLAB and PSS DE®Siemens provides similar findings. Highest loads are higher than assumed available power from grid, making energy storage essential. An implementation of BESS deliverers the safety needed to ensure security of supply. BESS capacity needed is highly dependent on grid subscription, and decreases with an increased grid. Implementation of PV is a source of self sufficiency and covers 4.8 % of the energy consumption over project timeline. PV contributes to reducing electricity costs, as well as providing income when sold to the grid, but is otherwise not necessary for a functioning energy system. Due to safety considerations at the airport, a simulation without PV was also executed.

Load increases were studied to ensure a flexible energy system without blackouts. Highest load increase without blackouts was 24 % in step 3. Energy storage batteries had a high state of health throughout the simulation. This ensures a long lifetime, also past simulation timeline. As the local grid is upgraded, the amount of energy storage can be reduced. The profitability of the project is highly dependant of income from charging, as the net present value ranges from positive to negative based on income assumptions. Financial support from government and sponsors is not included in the economic evaluations, but can decrease the dependency on income.

Further work should be performed to address the limitations set in this thesis. The research and development in this field has recently gained momentum and is continuously changing and improving. New technologies might change the premises this thesis is based on.

With the current grid capacity, Åre Östersund airport is not prepared for the duties of a test arena with the increase in power demand from commercial electric airplanes. However, with implementation of energy storage a sustainable energy system at Åre Östersund airport is fully realizable and an important step toward emission free aviation.

## Abstract in Norwegian (Sammendrag)

Luftfart er en viktig del av verdens kort- og langdistandemobilitet i dag og skaper store sosiale fordeler for verdens befolkning. Pågående elektrifisering av kommersiell luftfart har mål om å redusere de negative klimapåvirkningene fra industrien. Elektrifiseringen fører til stor økning i energibehov over hele verden og utfordrer kapasiteten i strømnettet. Green Flyway er et unikt nordisk samarbeid mellom Norge og Sverige og er en testarena for elektriske fly og andre luftfartøy. Prosjektet har fokus på å utvikle bærekraftig infrastruktur på flyplasser og å legge til rette for forskning.

Bacheloroppgaven tar for seg introdusering av ladestasjoner for elektriske fly i dagens flyplassinfrastruktur og har fokus på forsyningssikkerhet. Hovedmålet er å utvikle et bærekraftig energi- og ladesystem på Åre Östersund flyplass. Systemet skal simuleres over et tidsperspektiv på 20 år i MATLAB og PSS DE®Siemens. Simuleringen analyserer tre steg i elektrifiseringen av kommersiell luftfart. Det første steget er en testarena der små elektriske fly testes. I neste steg blir elektriske fly introdusert til det offentlige transportsystemet i buss-drift. Siste steg er buss-drift i kombinasjon med større elektriske fly med lengre rekkevidde.

Simuleringene i MATLAB og PSS DE®Siemens gir tilnærmet like resultater. Energilagring er nødvendig da høyeste last på flyplassen er større enn antatt abonnement på strømnettet. Introdusering av batteri som energilagring gir forsyningssikkerhet til systemet. Kapasiteten som trengs fra batteriene er svært avhengig av strømnettavtale og behovet øker jo mindre abonnement man har. Gjennom en solcelleinstallasjon får energisystemet selvforsyning av energi som dekker 4.8 % av energiforbruket gjennom prosjektets levetid. Solcellene bidrar til å redusere strømkostnader og er også en tilleggsinntekt ved at overskuddsenergien blir solgt til strømnettet. Utenom dette er energisystemet ikke avhengig av produksjonen fra solcellene for å fungere optimalt. Det er en risiko for at en solcelleinstallasjon på flyplassen ikke vil bli godkjent av myndigheter og det er derfor utført simuleringer både med og uten solceller.

For å forsikre at energisystemet kan tåle uforutsett last ble det utført lastøkningstester. Den høyeste lastøkningen systemet tålte var 24 % i steg 3. SoH var høy gjennom hele simuleringen. Dette forsikrer at batteriene har lang levetid, også etter at prosjektet er ferdig. Mengden energilagring som trengs i systemet kan reduseres dersom tilgjengelig kapasitet fra lokalnettet øker. Lønnsomheten til prosjektet er avhengig av ladeinntekt. Nåverdien til prosjektet varierer mellom positiv og negativ verdi avhengig av hvilke antagelser som gjøres om inntekt. Finansiell støtte fra myndigheter og andre aktører er ekskludert i økonomiske beregninger, men kan ha stor innflytelse på hvor avhengig prosjektet vil være av ladeinntekt.

Videre arbeid bør ta for seg noen av antakelsene som ble gjort i oppgaven. Forskning og utvikling i luftfartsindustrien er under stadig utvikling. Fremtidige teknologier kan påvirke premissene som ligger til grunn for denne oppgaven.

Med dagens strømnettavtale er ikke Åre Östersund flyplass klar for den store energietterspørselen som kommer når kommersielle elektriske fly skal testes på testarenaen. Det vil derimot være høyst realistisk å ha et bærekraftig energisystem på flyplassen ved å inkludere energilagring. Dette er et viktig steg i utviklingen mot utslippsfri luftfart.

# List of Terms

| Term | Explanation |
|---|---|
| Active Power | The power of which is actually consumed or utilized in an AC circuit |
| Airborne Shuttle Traffic | Airplanes working as airborne busses as part of the public transport system |
| Aircraft | Any object that has the ability to fly, either through mechanical means or via the forces of lift |
| Airplane | A fixed-wing aircraft that is propelled forward by thrust from a jet engine, propeller, or rocket engine |
| Albedo effect | Albedo is a measure of the reflection of a surface or a body. It is the ratio between reflected electromagnetic radiation and the incoming radiation. |
| All-electric airplane | Airplane with an electric engine with batteries as energy storage |
| Azimuth | A horizontal direction, given in degrees measured clockwise from a north base line |
| Blackout | A total crash of the power grid due to an imbalance between power generation and power consumption or controlled shutdown |
| Bottleneck | A point of congestion in a production system due to workloads arriving to quickly for the production process to handle |
| Bus | Depot connecting all elements in the microgrid |
| C-rate | The rate at which a battery can fully charge/discharge |
| CAPEX | Capital expenditures |
| $CO_2$-eq | A measurement for comparing the warming potential of different greenhouse gasses |
| Combustion | A chemical process in which a substance reacts rapidly with oxygen and gives off heat |
| Converter | Element converting electrical energy |
| CORSIA | A global offsetting scheme, whereby airlines and other aircraft operators will offset any growth in $CO_2$ emissions above 2020 levels |
| Cycle | The process of fully charging and discharging a battery |
| De-energized | To be disconnected from a source of electricity |
| Depth of Discharge | Percentage describing how deeply the battery is discharged |
| Discount rate | An interest rate used to determine the present value of future cash flows |
| Dopants | Devided into n-type and p-type dopants. N-type add negatively charged electrons to the semiconductors. P-type reduces the total negative charge of the semiconductor by stealing electrons. |
| Electric propulsion | The use of electrical power to accelerate a propellant by different electrical and/or magnetic means |

| **Term** | **Explanation** |
|---|---|
| Electrification | Transition from another form of energy to electricity |
| Electrode | The point at which an electric current enters or leaves an object, e.g. a battery |
| Electrolyser | A device which splits water into hydrogen and oxygen using electrical energy |
| End of Life | When a component reaches the end of its usefulness and/or lifespan and can no longer operate close to peak capacity |
| Energy Density | Amount of energy that can be stored by a device per unit of mass |
| eVTOL | Electric powered vertical take-off and landing aircraft |
| Green House Gas | Gasses which absorb and give off the heat energy emitted by the earth |
| Guarantee of origin | A guarantee of origin is an electronic guarantee that serves as documentation that electric power has been produced and delivered to the grid from a specified power plant. |
| Inverter | Element converting DC to AC |
| Irradiation | The process by which an object is exposed to radiation |
| Islanded mode | When a microgird is disconnected from the main grid and operates independently with micro sources and load |
| Licence | A set of rights and obligations of the holder of the licence, and is meant to respect environment and area issues |
| Microgrid | A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid |
| Net-Zero Carbon | Refers to the balance between the amount of greenhouse gas produced and the amount removed from the atmosphere. We reach net zero when the amount we add is no more than the amount taken away |
| OPEX | Operational expenditures |
| Peak power | Maximum power of a solar power installation. Calculate from AM1.5 corresponding to $\phi = 1000$ W/$m^2$. |
| Power tariff | Charge for highest power consumption |
| Reactive Power | By-product of power production due to imbalance between capacitive and inductive resistance |
| Rectifier | Element converting AC to DC |
| Residual Energy Mix | The mix of uncertified electricity, it is needed for reliable disclosure of electricity consumption where Guarantees of Origin are not used. |
| Security of Supply | The utility grids ability to deliver electrical energy to the end user |
| Self-sufficiency | Ability to maintain oneself or itself without outside aid |
| **Term** | **Explanation** |

| | |
|---|---|
| Semiconductors | Semiconductors have photovoltaic conducting properties , and are in group 14 in the periodic table. The band gap of PV semiconductors match solar wavelengths, so the material can absorb and convert the energy. |
| State of Health | A percentage describing the condition of a battery compared to its ideal conditions |
| State of Charge | The percentage of the battery capacity available for discharge |
| Specific Energy | Energy content per unit mass |
| Specific Power | Power per unit mass |
| Substation | Station containing one or several distribution transformers, in addition to low-voltage and high-voltage switchboard plant |
| Svenska Kraftnät | A state-owned electricity transmission system operator in Sweden |
| Tilt Angle | The angle between the surface of the PV module and the horizontal surface |
| Transformer | A passive component that transfers electrical energy from one electrical circuit to another circuit |
| Uninterrupted power supply | An electrical apparatus that provides emergency power to a load when the input power source or mains power fails. |

# List of Symbols

| Symbol | Explanation | Unit* |
|---|---|---|
| $\eta$ | Efficiency | [%] |
| $\phi$ | Irradiation | [$W/m^2$] |
| $A$ | Area | [$m^2$] |
| $B_N$ | Future savings | [SEK] |
| $C_{rate}$ | C-rate | |
| $E_0$ | Theoretical maximum energy capacity | [kWh] |
| $E$ | Energy capacity | [kWh] |
| $I_{BE}$ | Cash inflow in the break-even year | [SEK/yr] |
| $I_N$ | Investment costs | [SEK] |
| $I_P$ | Cash inflow preceding year | [SEK/yr] |
| $L$ | Number of cycles in a lifetime | |
| $NPV$ | Net Present Value | [SEK] |
| $PP$ | Payback period | [yr] |
| $P_{W_P}$ | Peak power | [W] |
| $r$ | Discount rate | [%] |
| $R$ | Amount left to be recovered | [SEK] |
| $S$ | Residual value | [SEK] |
| $SoC$ | State of charge | [%] |
| $SoH$ | State of health | [%] |

*Empty cells are dimensionless

# List of Acronyms

| **Acronyms** | **Definition** |
|---|---|
| AC | **A**lternating **C**urrent |
| ATM | **A**ir **T**raffic **M**anagement |
| ATS | **A**pplicant **T**racking **S**ystem |
| BESS | **B**attery **E**nergy **S**torage System |
| BEV | **B**attery **E**lectric **V**ehicle |
| BMS | **B**attery **M**anagement **S**ystem |
| BOS | **B**alance **O**f **S**ystems |
| BSc | **B**achelor of **S**cience |
| CCS | **C**arbon **C**apture **S**ystem |
| CFP | **C**arbon **F**oot**p**rint |
| CHAdeMO | **Cha**rge the **Mo**ve |
| CHP | **C**ombined **H**eat and **P**ower plant |
| CtG | **C**radle to **G**ate |
| DC | **D**irect **C**urrent |
| DoD | **D**epth of **D**ischarge |
| EMI | **E**lectro**m**agnetic **I**nterference |
| EoL | **E**nd of **L**ife |
| EP | **E**lectric **P**ropulsion |
| EPBT | **E**nergy **P**ay**b**ack **T**ime |
| EPS | **E**mergency **P**ower **S**upply |
| EROI | **E**nergy **R**eturn **O**n **I**nvestment |
| ESS | **E**nergy **S**torage **S**ystem |
| EV | **E**lectric **V**ehicle |
| FAA | **F**ederal **A**viation **A**dministration |
| GHG | **G**reen **H**ouse **G**as |
| HF | **H**ydrogen **F**louride |
| LCO | **L**ithium **C**obalt **O**xide |
| LFP | **L**ithium iron **P**hosphate |
| LiB | **L**ithium **i**on **B**attery |
| LPV | **L**ocalizer **P**erformance with **V**ertical guidance |
| MSB | **M**yndigheten för **S**amhällsskydd och **B**eredskap (Swedish Civil Contingencies Agency) |

| **Acronyms** | **Definition** |
|---|---|
| NMC | **N**ickel **M**anganese **C**obalt |
| NOK | **No**rwegian **k**roner |
| NPV | **N**et **P**resent **V**alue |
| PCC | **P**oint of **C**ommon **C**oupling |
| PEMFC | **P**roton **E**xchange **M**embrane **F**uel **C**ell |
| PV | **P**hoto**v**oltaic |
| PVGIS | **P**hoto**v**oltaic **G**eographic **I**nformation **S**ystem |
| SAE | **S**ociety of **A**utomotive **E**ngineers |
| SEK | **S**w**e**dish **K**ronor |
| SMHI | **S**wedish **M**eteorological and **H**ydrological **I**nstitute |
| SoC | **S**tate **o**f **C**harge |
| SoH | **S**tate **o**f **H**ealth |
| SVK | **Sv**enska **K**raftnät |
| TAT | **T**urn **A**round **T**ime |
| UAS | **U**nmanned **A**erial **S**ystem |
| UTM | **U**nmanned aerial systems **T**raffic **M**anagement |
| UPS | **U**ninterrupted **P**ower **S**upply |
| VAT | **V**alue **A**dded **T**ax |

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# 1 Introduction

In order to reduce aviation's impact on climate change and meet the sustainable development goals, growth towards a sustainable aviation industry has commenced. The purpose of this bachelor thesis is to design a sustainable and secure energy system to meet the growing power demand at airports when implementing charging of electric planes. The thesis is written in collaboration with Siemens AS and Green Flyway. A description of the background and motivation for electrification of Nordic aviation is given in this chapter.[1]

The Paris agreement established in 2015 is a legal agreement between all UN member countries. The goal is to limit the temperature rise in the world to 1.5 °C, committing to a world wide reduction of greenhouse gas,GHG, emissions. The European Commission recently launched a goal of reducing emissions from the transport sector with 90 % by 2050. In January 2019, the *Declaration on Nordic Carbon Neutrality* was signed by all Nordic prime ministers and ministers of environment. This declaration commits the Nordic countries to work together to attain carbon neutrality.[2–4]

A large part of the declaration is to reduce GHG emissions from the transport sector by improving energy efficiency, using renewable fuels and electrifying various transport modes. Sweden is already in the front line regarding biofuels in road transport, while Norway is leading in electrification of cars and ferries. The transport sector directly employs 10 million workers and contributes to 5 % of European gross domestic product.[3–5]

The number of electric cars on Norwegian roads in proportion to other vehicles makes Norway the country in the world with largest share of electric cars. The charging infrastructure is well developed and there are strong financial incentives for purchasing electric cars. Ampere, the first electric ferry in Norway, has been in operation since 2014. The increasing share of electric ferries has made Norway a leader within electrification of the maritime transport industry.[6, 7]

The aviation sector is responsible for 2 % of global GHG emissions today. This number is expected to increase to 15–27 % by 2050. Contribution of different measures to reduce net $CO_2$ emissions from international aviation is illustrated in a future perspective in figure 1.1. It shows the presumed reduction caused by measures like operational improvements, aircraft technology, and sustainable aviation fuels and GHG emission quota system called CORSIA.[4, 8]

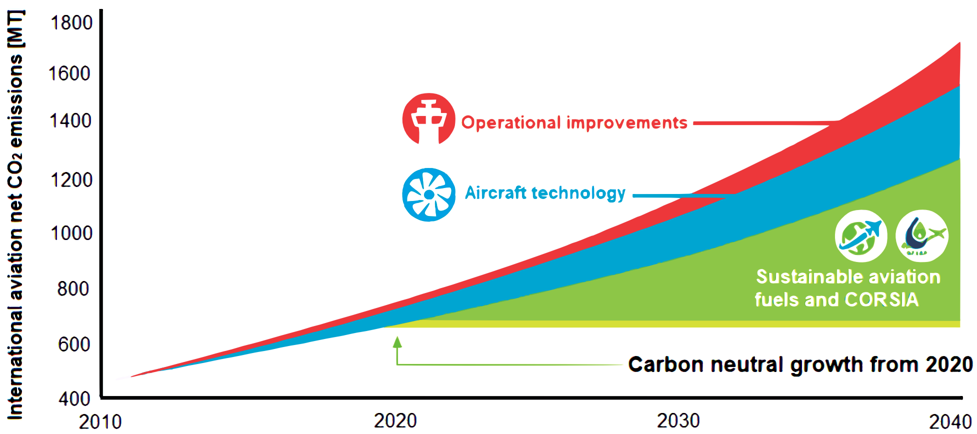


**Figure 1.1:** Future prospects of measures to reduce net $CO_2$ emissions from international aviation.[8]

Small electric planes have been flown since the 1970s and the first hydrogen powered vessel was flown by NASA in 1957. Today, aviation is a crucial component in the long-distance mobility in the world and provides important social benefits. Aviation has a downside of significant negative impacts on climate and environment. Aviation is a source of local pollution and high noise levels around airports today, which will be reduced by using electric planes.[9, 10]

Sweden aims to have fossil free domestic aviation by 2030, while Norway aims for 100 % electric domestic aviation by 2040. These goals make Sweden more flexible regarding use of sustainable fuels. Electric planes contribute to achieve goal 7 through 9, 11 and 13 of the United Nations' Agenda 2030 goals. It will help reduce global emissions, develop a sustainable and innovative industry, and contribute to higher interaction between cities and rural areas. The idea is that electric aircrafts in the future will be able to be used at shorter distances and contribute to reduce GHG emissions. Electrification also reduces other negative consequences from fossil fuel like noise from the combustion engines and release of contrails and particles.[4, 9–11]

In 2018, passenger flights were responsible for 81 % of aviation emissions, while cargo flights was responsible for the remaining 19 %. About 40 % of emissions from passenger flights come from domestic flights. There are large global inequalities from countries with different income levels when it comes to emissions from aviation. Populations living in the highest income countries accounts for 16 % of the world population, but are responsible for as much as 62 % of the total $CO_2$ emissions from air travel. The lower-middle income population accounts for 40 % of the worlds population and is responsible for only 9 % of the total $CO_2$ emissions. These inequalities are illustrated in figure 1.2 alongside upper-middle income and lower income countries.[12]

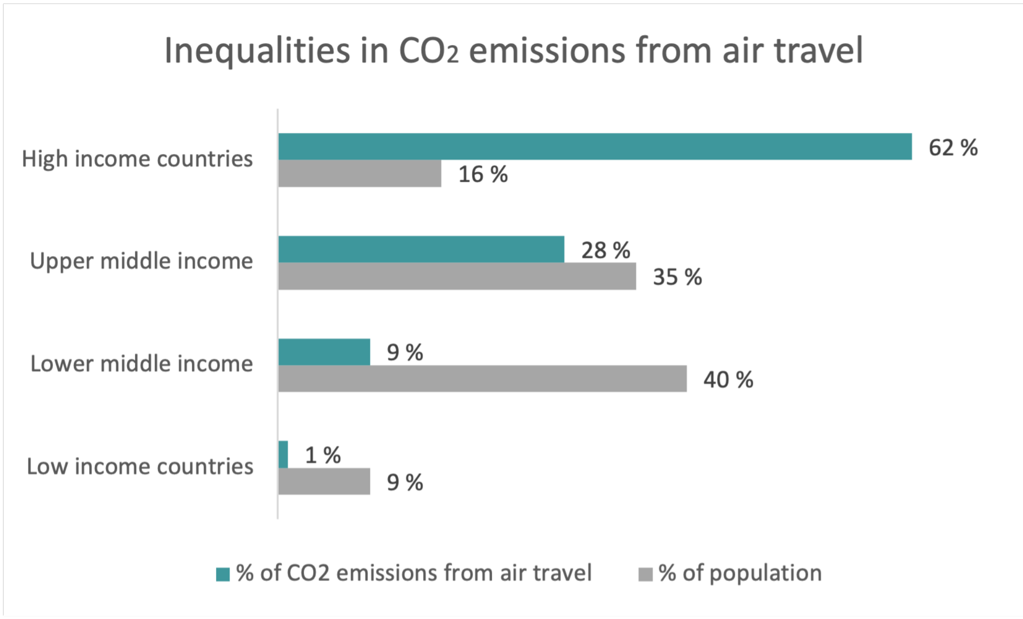


**Figure 1.2:** Global inequalities in $CO_2$ emissions from air travel based on income groups.[12]

Electrification of the aviation sector has the potential to cut major parts of both global and local emissions. The climate impact from aviation within the Nordic countries can be significantly reduced using electric or hybrid planes on short-distance routes. The development in sustainable aviation technologies could also contribute to reduce emissions on medium- and long-distance routes. The European Commission states that zero-emission large aircraft will be ready for the market by 2035.[4, 5]

There are several reasons why Norway and Sweden are suited for electric aviation. Both Avinor and Swedavia have a large airport network. Today, short-distance routes are flown with relatively few passengers per flight in both countries. This is particularly suitable for testing of the first commercial electric airplanes that have limited range and capacity. Both countries have given political support to establish framework conditions contributing to electrification. The energy mix in both countries also have a large proportion of renewable energy production.[4, 13]

Avinor has a vision that all civil domestic aviation in Norway is electrified by 2040. The goal is to become the first market where electric airplanes have a significant market share. These assessments are based on the possibility that small, fully electric airplanes with limited range are developed for commercial use by 2025. When it comes to Avinor airports, GHG emissions are visioned to be halved by 2022 compared to 2012, and airport operations to achieve net-zero carbon emissions by 2030.[13, 14]

Swedavia had a goal of zero $CO_2$ emissions from their own operations by the end of 2020. The emissions decreased with 97 % from 2005 to 2019, and the goal was reached in 2020. The reason for this decrease is enhanced energy efficiency parallel with replacing fossil fuels with renewable fuels, using biofuels or renewable district heating. Biofuels are also a large contributor to achieve fossil free domestic aviation in Sweden by 2030.[15]

Several airports in Norway and Sweden are working towards sustainable infrastructure and possibilities of implementing sustainable airplanes. The western parts of Norway are especially suited for electric airplanes. The distances are great and the topology can be challenging for other transport means. Sola airport in Stavanger works towards becoming a sustainable airport and is already implementing charging of electric cars and buses. They aim to be self-sufficient with renewable energy by the end of 2025. Another goal is to have a commercial electric route between Sola airport and Flesland airport in Bergen by 2025.[16, 17]

The aviation industry has grown substantially in the last decades, up until Covid-19 spread globally. The pandemic has led to a drastic and unpredicted decline in the number of international and domestic flights which has caused an economic crisis within the aviation industry. The duration of the pandemic and the consequences it will cause nationally and internationally is uncertain. It affects both demand and supply which can lead to a delay in aviation investments.[4]

## 1.1 Case Definition

This report is written as a part of the Green Flyway project and is issued by Siemens AS. Case description was developed in collaboration with Siemens and considers thoughts and inputs from contributors in the Green Flyway project. The developed case definition is:

*Design of a resilient and sustainable local energy system at Åre Östersund airport, integrating charging of electric planes.*

The bachelor thesis will address the current and future situation at Åre Östersund airport. The airport is aiming for a sustainable energy system with security of power supply. Today there are two diesel-powered generators used for emergency power supply at the airport that are going to be replaced with a sustainable solution. A high-capacity renewable energy storage system must be implemented because of extensive increase in the energy consumption due to development and implementation of electric planes.

The simulation will be handled using a timeline with different flight patterns and energy system components according to future development in the aviation industry. Each step in the timeline is a step in the future development at the airport. Charging sequences for electric planes for each step is chosen based on theory on commercialization of electric planes, but can happen more rapidly or be delayed. The main purpose is understanding energy and power demand. The energy system components considered are power extracted from the grid, batteries or hydrogen used for energy storage and solar cells used to produce local renewable energy. The number of batteries and grid subscription will be alternated to fit the development of each reference point. Some values have been omitted from the assignment due to a confidential information agreement with Northvolt.[18]

## 1.2 Contributors

This bachelor thesis has been dependent on information retrieval and support from various contributors. Information was gathered via mail and digital video conferences. An overview of the contributors is presented below.

Siemens AS is the main contributor and client on this thesis. Siemens is the world's largest contributor of sustainable and environmentally friendly solutions and groundbreaking technologies. The company delivers innovative technology to all industry fields. They focus on energy production and distribution of electricity to smart grid solutions, and transport solutions and construction.[19]

Other important contributors on information gathering are Swedavia AB, Jämtkraft AB and Northvolt AB. Swedavia owns and operates a large network of airports in Sweden. Jämtkraft is the operating energy company in Östersund. Northvolt is a Swedish battery developer and manufacturer who specialized in lithium-ion technology. Several other businesses have also contributed with valuable information. All contributors are listed in table 1.1.[20–22]

**Table 1.1:** Contributors to the BSc thesis

| **Names** | **Company** |
|---|---|
| Fredrik Karlstedt | Frösö Park |
| Martin Brunstad Høydal | GETEK |
| Hans Dunder | Green Flyway |
| Caroline Hildahl | Jämtkraft |
| Thorsten Handler | Jämtkraft |
| Jimmy Anjevall | Jämtkraft |
| Bjørn Thorud | Multiconsult |
| Jasmin Noori | Northvolt |
| Elias Afeiche | Northvolt |
| Anne Sörensson | Östersund Municipality |
| Kari S. Tærum | REC Group |
| Sandra Alstad | Siemens Energy |
| Kaushik Jayasayee | SINTEF |
| Håkan Pedersen | Swedavia |
| Hanna Rudeklint | Swedavia |

## 2 Green Flyway and Åre Östersund Airport

Green Flyway is a unique Nordic partnership between Norway and Sweden. It is a project with focus on the future of aviation and works as a test arena for electric airplanes, unmanned aerial systems UAS, eVTOL and ground support. The idea is to develop an infrastructure where research and testing can be carried out, both on land and in the air. The research done by Green Flyway also includes optimal design of charging equipment and airport infrastructure.[23]

The duration of the project is set from the 20th of November 2019 to the 30th of September 2022, and it is expected that new projects will develop in the future. Norway has funded the project with 5,57 million SEK and Sweden has funded with 14,2 million SEK. Various companies from both countries are involved in the project. The main test arena is the airspace corridor between Røros airport in Norway and Åre Östersund airport in Sweden.[23, 24]

A smaller test arena with a focus on research related to energy consumption, storage and transportation is located in Trondheim. All airports in the Green Flyway project are supplied with renewable electricity. The local energy companies, Jämtkraft in Sweden and Ren Røros in Norway, are working in close relations with the project.[23, 24]

Åre Östersund airport was opened in 1926. In a normal year about 500 000 passengers pass through the airport, making it Sweden's eight largest airport. The runway is 2500 m long. Åre Östersund airport and partner Frösö Park is shown in figure 2.1.[23, 25]


**Figure 2.1:** Green Flyway test arena site, Östersund, Sweden.[23]

The main goal is to establish test arenas for electric aviation and make the arena capable of operating at own commercial merits after the project is completed. Ground based test arenas at the airports are important in order to establish potential solutions for air traffic management and charging infrastructure. The design and quality of the test arenas are determined in cooperation with authorities, producers and subcontractors. The focus is also on developing a system where electric aviation is integrated in today's industry.[24]

Green Flyway explores the potential for regional development enabled by electric aviation. Test flights are executed between Åre Östersund airport and Røros airport with a distance of approximately 175 km. It is a large airspace corridor available for testing with minimal interfering by other air traffic. Nordic climate and challenging mountain terrain provide Green Flyway a unique test environment compared to similar projects in warmer climates. Figure 2.2 shows relevant locations for the project. Östersund, Sveg, Røros and Trondheim are test arenas in the project, while the other locations are presumed to be relevant flight routes.[24]

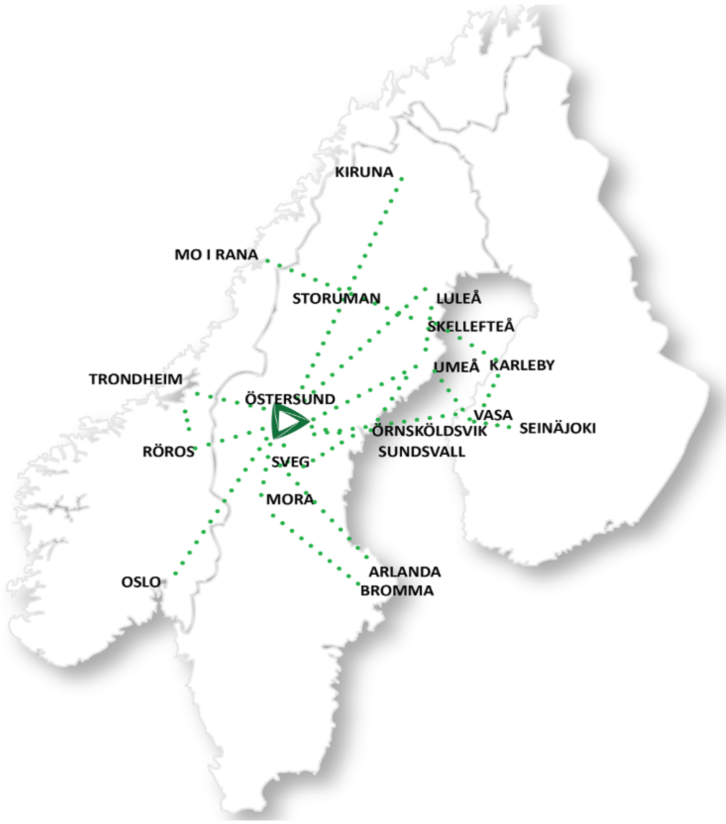


**Figure 2.2:** Locations relevant to the Green Flyway project and potential flight routes.[24]

## 2.1 Future Plans

Countries with geographical distances and varied landscape like Norway and Sweden are very dependent on air travel. There is a focus on reducing emissions from air travel, not air travel itself. The vision of emission free aviation consists of measures in technology and fuels, efficient traffic management, improved airport infrastructure and marked-based actions.[26]

Located in Östersund is an aero club where pilot training is administered. It has the possibility of being expanded to meet the need for new pilots capable of operating electric and hybrid planes and drones. Green Flyway, with Åre Östersund airport, Frösö Park Arena and Östersund aero club, has the potential and capacity to become an international test arena and training center for electric airplanes. Östersunds location and climate is highly relevant and valuable to many projects wanting to test their technology in arctic conditions. Östersund and Sweden can also offer clean electricity.[26]

International users of the test arena will benefit the Green Flyway project and the local businesses. Being a test arena for electric flying entails that Östersund must be ready to accommodate a large number of people. They must also be able to provide a variation of fuel options for different type of projects, such as bio jet-fuel and hydrogen. The vision is to be a test arena for electric and sustainable aircrafts similar to what Arjeplog is for cars. In Arjeplog, thousands of car manufacturers visit every year to test their cars in arctic conditions.[26]

The installation of needed infrastructure at Åre Östersund airport and Røros airport is expected to happen in the near future. This makes the airports ready to start testing and flying short-haul 9 to 19 seat all-electric and hybrid airplanes. There is a vision of an electrified bus connection with wings, referred to as airborne shuttle traffic. Östersund and Røros will serve as connection points between a number of cities and towns in Norway, Sweden and possibly Finland. On airplanes with less than 20 passenger seats there is no requirement to pass through the security lines at the airport. The efficiency of not being dependent of passing through security is vital for airborne shuttle traffic to work.[26, 27]

In the future the airports need to be ready to accommodate and charge large electric planes capable of flying long range. All-electric airplanes capable of flying long distances are limited by the weight of the batteries, and will likely not be available, at least for a couple of decades. It is hydrogen powered and hybrid-electric airplanes that are most relevant to replace the current traffic for long distance flight.[27]

## 2.2 Safety Considerations at Airports

Energy systems at airports have a high electricity demand. Due to the critical position of national and regional airports, a reliable power supply is crucial. To ensure the safety and operation of flights an airport requires a minimum level of power to always operate critical components. The electricity usage of an airport can roughly be separated into landside and airside. Landside consists of terminal and external parking structure, and airside consists of the airstrips and control- and communication buildings. The landside of the airport is responsible for about 60 % of airport energy consumption, and the airside for the remaining 40 %.[28, 29]

An airport is considered critical infrastructure on a local, regional or national scale, depending on the status of the airport. The airport and air traffic is a part of the transport sector of a nation's important communal functions. The protection of critical infrastructures refers to measures and actions implemented to ensure functionality and continuity. The purpose is to increase the infrastructures' ability to withstand and recover from disturbances.[30]

The Swedish Civil Contingencies Agency has created a model describing guidelines for protecting airports. It illustrates areas needing protection, threatening factors and responder guidelines as shown in figure 2.3.[30]


**Figure 2.3:** Model with guidelines for protection and safety at airports. Edited from original.[30]

Every airport has an emergency power system available in case of blackouts. It is required to cover the runway systems that are used under difficult weather conditions. The backup-power is required to meet the capacity of the following equipment:[31]

1. Signal lights and minimum lighting for air traffic controllers
2. All obstruction lights at and near the airport necessary for safe aviation
3. Lightning systems for approach, runway and taxiway
4. Meteorological equipment
5. Essential equipment and facilities for emergency services connected to the airport
6. Headlight lighting in a separate parking space for aircrafts

The reserve power supply should be able to supply the necessary lights and the navigation facilities for the time required to phase out the current traffic. The power supply must be connected in a way that it is automatically switched on when there are faults in the normal power supply. Different components of the system have different time requirements to react. Most of them have a limit of 1 to 15 seconds.[31]

There are mainly two types of emergency power supply, generators and uninterrupted power supply UPS. They can work together or separately to ensure security of supply. Generators are powered by diesel or gasoline, which is stored in containers. A generator can provide power for a long amount of time, and is only limited by the amount of fuel available. A UPS provide instantaneous power when the normal source malfunctions, and reacts faster than a generator. It can store electricity in different technologies, such as batteries and fly wheels. Fly wheels use a spinning mass to generate electricity. A benefit of using UPS as emergency power is that it can also balance voltage and work as a frequency regulator.[32]

Historically UPS were not capable of supplying the needed capacity and were only used for a short amount of time. Recent technologies now offer battery packs and large-scale fly wheels to replace the fuel-powered generators. Additionally, newer and more sustainable technologies are coming, such as more environmentally friendly fuel for generators and hydrogen storage. These can replace the energy capacity of fuel powered generators but will potentially require more space.[32]

### 2.3 Taxes and Fees at Airports

Sweden and Norway both have carbon emission charges on domestic flights. The Swedish rate is at 1190 SEK/tonne $CO_2$-eq, and the Norwegian is 552 SEK/tonne $CO_2$-eq. Norway also have an electricity fee rated at 0.156 NOK/kWh for parked planes. This fee is reduced for charging of electric marine vehicles, this will likely be reduced for electrical aviation as well.[33, 34]

Swedavia and Avinor has additional charges in place at their airports. These include take-off charge, emission charge, noise charge, aircraft parking charge, passenger charge, ground handling infrastructure charges, fuel handling infrastructure charge and security charge.[35]

The emission charge placed by the airport is based on emissions during approach, taxi, take-off and climb. It covers control, measurements and reducing measures for emissions at the airport. The noise charge covers monitoring systems and reduction of noise levels. It is calculated based on airplane certificated noise level. The fuel handling infrastructure charge covers the cost of centralized infrastructure for fuel handling.[35]

The UN organization ICAO has introduced a quota system on GHG emission to reduce impact of international air travel, called CORSIA. At least 78 states, including Sweden and Norway have committed to the system, and it will be implemented through an EU directive. Initially, CORSIA represents a demand to report emissions from international flights. From 2024 aviation operators will have to compensate for the increased emissions compared to 2020. Aviation operators have to buy and cancel emission-units. These represent emission reductions in other sectors to make up for the increase in emissions.[33, 36]

# 3 Electric Planes and Charging Options

Research and development of electric airplanes have gained momentum the last few years. There are close to 200 projects and initiatives dedicated to make air travel more sustainable. An electric plane is a collective name of both all-electric and hybrid planes that uses one or more electric motors, as shown in table 3.1. It is differentiated between engine technology and energy source technology.[33]

A battery electric airplane is further referred to as a all-electric plane, and describes a plane that runs on an electric engine with batteries as the only energy storage. A hybrid airplane runs with an electric engine with both battery storage and a second energy source. It can be jet fuel or hydrogen converted into power through a turbine or a fuel cell, respectively. The hybrid systems may be connected in parallel, but in the case of fuel cells it may also be connected in series, as a range extender.[33]

**Table 3.1:** Variations in engine and energy source combinations for electric planes.[33]

| | Battery electric | Serial hybrid | Parallel hybrid | Fuel cells |
|---|---|---|---|---|
| **Engine** | Electric | Electric | Electric + Conventional | Electric |
| **Energy source** | Battery | Battery + Fuel cells $/H_2$ | Battery + liquid fuel | Fuel cells$/H_2$ |

Electric engines mostly run on electric propulsion which uses electrical power to accelerate a propeller. It differs from conventional systems in that it requires smaller amount of mass to accelerate. An electric engine can use e.g. batteries and fuel cells as energy source. There are also sustainable airplane projects that use a conventional engine. With minimal adjustments the conventional airplane engine can use more renewable fuel options as energy source, such as hydrogen and bio-fuel. A timeline of expected technology and range for electric planes is shown in figure 3.1.[33, 37]

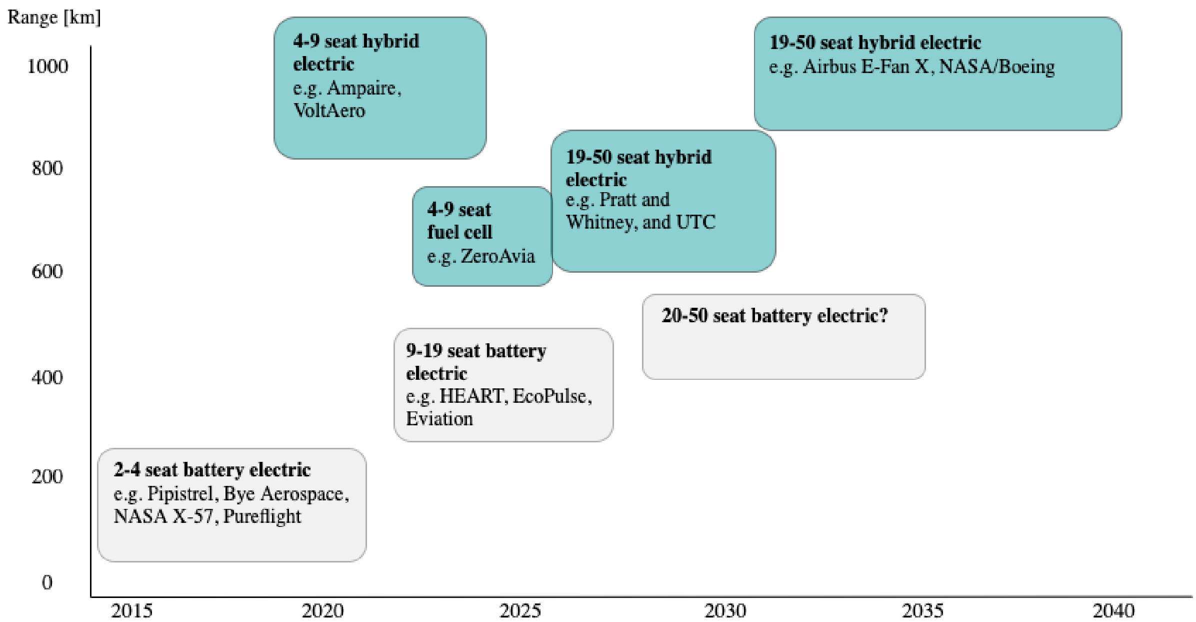


**Figure 3.1:** Timeline for expected technology and range of electric planes. Edited from original.[33]

Today there are small all-electric and hybrid planes already in use. By 2025, it is expected that multiple planes will be tested and ready for commercial use. The planes will vary between 4 and 20 seats, with a range of 400 to 1000 km. With the current technology there are reservations for developing all electric planes that can seat more than 50 people with a range over 500 km. Planes using hybrid technology are expected to replace the current air traffic.[33]

At the rate of evolution today, there are many uncertainties of the requirements of infrastructure and components. The biggest challenge related to using battery as energy storage in airplanes is the weight. Batteries have an energy density that limits the capacity. Fossil-fuel has 40 to 60 times higher energy density than current batteries. However, conventional jet engines have an energy efficiency of 30 to 40 %, while electric engines have an energy efficiency up to 100 %. In addition to using hydrogen in fuel cells as energy storage, it can also be used as liquid fuel in modified conventional engines.[10]

## 3.1 Green Flyway Planes

The Green Flyway project has acquired two electric two seat airplanes, a Phinix and a Pipistrel, to use as test planes. In addition, one of the partners in the project is Heart Aerospace, which is in the process of developing a 19–seat electric airplane. In the future the larger electric planes are expected of have a considerably higher energy demand. The airplanes currently involved in the project are all-electric, not hybrids.[24]

### Pureflight Phinix

The Phinix is a two seat plane by the company Pure Flight, the plane is shown in figure 3.2. The airplane runs on a propulsion system, with an engine power of 60 kW. The estimated flight range is 2.5 hours with a charging time of 20 minutes to 85 %. This electric plane is used by Green Flyway as a test for landing and flying in different weather conditions. Initial test-runs with the Phinix test-plane were run in February of 2020. It flew between Sveg in Sweden and Røros in Norway, with a total distance of 219 km. It had an intermediate stop in Funesdalen on an airstrip on a frozen lake.[38, 39]


**Figure 3.2:** Two seat Pureflight Phinix plane acquired by Green Flyway.[40]

The phinix is charged using the pure charge system. Pure flight offers three different chargers, meeting different requirements. A supercharger which can charge a plane up to 80 % in 20 minutes. A fast charger with the ability to charge a plane in a couple of hours, and a portable charger that can charge the plane over night and be brought along on the plane.[38]

### Pipistrel

The Pipistrel has a 60 kW engine with a 21 kWh battery pack. It is optimized for flight training, with short take-off and landing distance and endurance of approximately one hour. The Alpha Electro model was the first two seat electric trainer in the world. The battery pack is designed to either be quickly replaced and swapped, or charged in less than one hour.[41]

### Heart Aerospace ES-19

Heart Aerospace was founded in 2018, with a mission to design and develop an all-electric airplane. ES-19, a plane carrying 19 passengers, will be ready and authorized for commercial flight by 2026. The plane is shown in figure 3.3. It will have a range of 400 km, and be able to take off and land on 750 m runways, making it optimal for smaller airports and routes. The airplane operates with an all-electric propulsion system and is made with a lightweight aluminum airframe. Heart Aerospace´s ES-19 is currently under development and will likely have energy storage of about 1 MWh. They have not decided on a charging connector.[42]


**Figure 3.3:** 19 seat ES-19 by Heart Aerospace, partner in Green Flyway project.[42]

## 3.2 Charger Options

The charging speed is dependant on different factors like type of charger, size of the fuse, temperature and the EV model. Charging of electric cars can roughly be divided in four main types, as shown in the table 3.2 below. In addition there are multiple chargers that can deliver over 1 MW power under development. The power output of different charger types for airplanes will differ from cars, because of the varying size. For an ES-19, fast charging will entail a charging output with much greater power than for electric cars.[43–45]

**Table 3.2:** Power output of different charger types for electric cars.[43]

| | |
|---|---|
| Slow AC | 3.5 kW |
| Fast AC | 7 kW - 22 kW |
| Rapid AC | 43 kW |
| Rapid DC | 50 kW - 350 kW |
| Expected mega DC | 1 MW → |

Slow charging of electric cars uses three-phase AC-current from the grid. When charging with AC-current the converter in the electric vehicle, EV, is the limiting factor. With slow charging it typically takes an EV 8–12 hours to charge, making it commonly used at private residences for over-night charging and at workplaces. Fast chargers are typically rated at 7 or 22 kW with single or three-phase 32 A, mostly using AC. Rapid charges range from 50 kW to 350 kW, mainly using DC current and can charge an EV in 2–5 hours. When charging with DC current, the current is added directly to the battery, while charging with AC-current passes through an on-board converter to DC. Rapid charging can cause strain on the battery and reduce the lifetime and safety if done too often.[43, 46, 47]

### Charging Standards of EV

To be able to charge at different locations there are standards of charging points for EVs. As a result of different car manufacturers and continents using different connectors, there are several charging standards for electric cars. Some of the most common connectors for DC fast charging are CHAdeMO, combined charging system, and Tesla Supercharger.[48]

As electric airplanes are under development, a committee is assembled to develop one international charging standard. There are more than 100 designs and developments underway for electric planes, and the committee works to make the charging as safe and efficient as possible. Multiple electric plane manufacturers are waiting to decide on a charger connector for a charging standard to be established.[27, 49]

A common standard of charging, design and safety at the different airlines must be established. If a fire does occur, one must know the exact placement of the battery pack in the plane and how to access it. Similar flushing holes and ventilation in all batteries are important, as well as a way to make sure the plane is de-energized. The location of the main power switch and fuses, in addition to location and color of high voltage cables should also be common. This is an area that needs to be further researched. The risk factors must be mapped in order to implement measures to reduce the risks. Responders should also be educated on the risks and how to handle them.[47, 50]

### Charging of Heavy-Duty EV

Most heavy-duty EV currently have two charging options, faster DC charging or lower AC charging for over-night charging. With the chargers on the market today, most trucks need over one hour to charge. To charge heavy-duty EVs in under one hour requires a charger with a power output of over 1 MW. There is also no charging standard for bigger vehicles, however there are multiple companies working on creating one.[51]

Among the developers is the forum CharIN responsible for the combined charging system standard for smaller EVs. They are now developing megawatt charging system, MCS, standard that has a charging power of around 4 MW. The application of this charger is mainly for trucks and busses, however the necessary requirements for marine and aviation is being implemented. Another contender for the charging standard for larger EVs is ChargePoints's mega charger. Chargepoint has introduced a 2 MW charge connector intended for electric planes and semi-trucks.[44, 45, 51]

Chargers delivering over 1 MW power will most likely be very heavy, and connecting the charger to the EV could be challenging. It is possible that the charging of the planes will have to be automated and hands free. Some ferries use a robotic arm to connect the charger to the vehicle, other use induction.[52]

### Charging of Electric Planes

Today there are three main options when charging an electric plane. The first is charging from the airports local grid, and secondly charging from stationary energy storage system, ESS, at the airport. The last option is to use swappable batteries, where the plane swapps its partially discharged battery for a fully charged battery at the gate. The three options are illustrated in figure 3.4. The swapping method demands that there are available fully charged batteries at every airport the plane lands at, and that multiple airlines and planes types uses the same type of battery.[33]

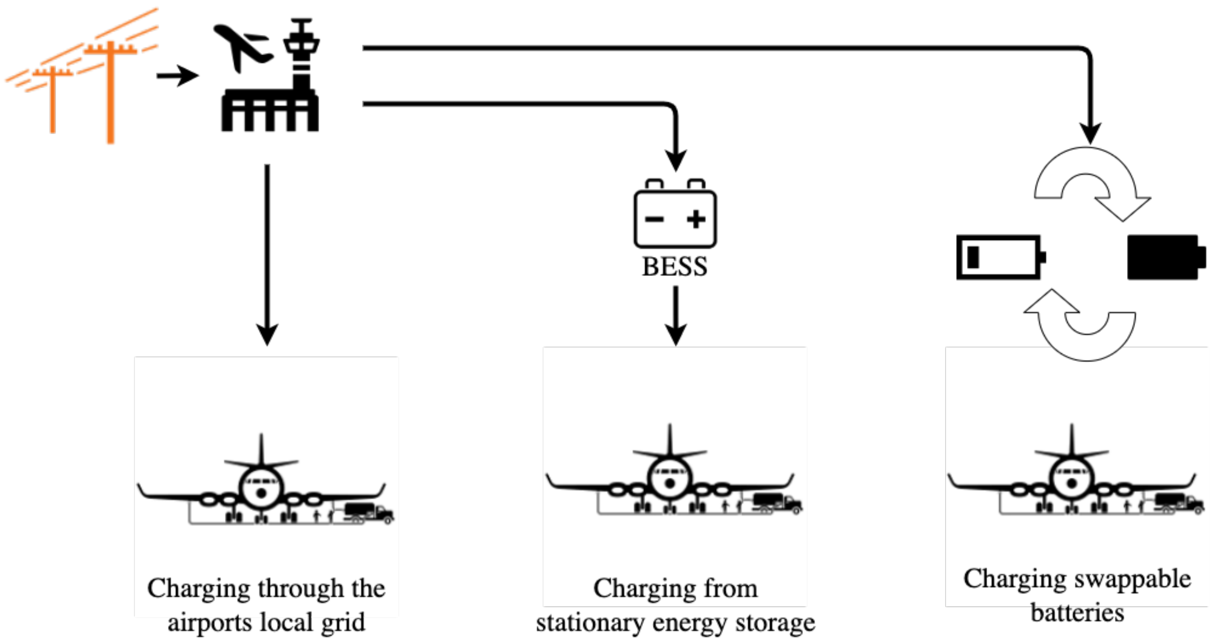


**Figure 3.4:** Three main options for charging electric planes at an airport.[53]

In aviation the charging time is very important. Turnaround time, TAT, for most airplanes is around 1 hour, while some low-cost airlines have managed to lower TAT to around 30 minutes. To airlines, every reduction in TAT increases revenues, and efficiency is of utmost importance. To make electric planes eligible to replace many of the airplanes on the market today, they have to be able to fully charged in under one hour. For airplanes with battery packs larger than 500 kWh, they will need chargers that are able to deliver more than 1 MW.[51, 54]

# 4 The Swedish Power Supply

Electricity production and consumption happen instantaneously and must always be in balance. Energy production and consumption does not happen in the same place, and it is not possible to transport more than the power grid can withstand and is dimensioned for. The energy consumption in the world is increasing, with electrification of the transport sector, industry, data centers, battery factories and hydrogen production. In addition, the increased fast charging of electric cars adds pressure to the power lines. Today most of the energy sources in the Nordic countries are weather-dependent, making the balance between production and consumption uncertain and demanding.[55]

The main Swedish power grid transports power over long distances, before it branches off to regional and local grids. The grid connects all power suppliers and users, and connects across borders. The main transmission network has a voltage of 220 kV or higher. Svenska Kraftnät, SVK, is the state-owned organ in charge of operating the transmission system. Regional and local networks have lower voltages and are owned and operated by distribution network operators. Figure 4.1 shows the transmission network in Scandinavia. The red lines are 400 kV-cables and the green are 220 kV-cables.[56, 57]


**Figure 4.1:** The Swedish transmission net with connections to surrounding countries.[58]

Sweden is divided into four power areas to help control production and consumption of electricity in the country. The borders for the areas are set in the bottlenecks in the power grid. The northern parts of the country have high production and low consumption, and the opposite in the south. This leads to higher electricity prices in the southernmost areas of the country. Power-intensive industries are encouraged to establish in the north, and power producers in the south.[59]

SVK has in recent years gone from mainly administrating the grid to extensive grid investments. Large parts of the Swedish grid are older than 40 years and is in need of upgrading. The investments have been necessary to be able to meet the increasing energy demand and upgrade an old Swedish grid. If the consumption is concentrated around the hours most electricity is used, the grid capacity needs to increase. This investment means increased costs and higher grid fees. Grid fee is a cost the consumers pay to finance the power grid. It covers SVK's operational and maintenance costs and compensates for any losses on the grid. This contributes to efficient development and utilization of the power grid.[55, 60, 61]

Subscribers of the grid are charged based on electricity use, energy use and an external cost if overrunning the subscription. If the consumer exceeds its subscription, a fee of 2800 SEK/MW must be payed for the exceeded amount of power after three hours. After the first hour of overrunning the subscription, 20 % of the total fee must be payed. After two hours 50 % of the total fee must be payed.[62]

The power companies are obligated to show the environmental impact of the electricity they sell. In order to guarantee the origin of the electricity sold, electricity traders buy guarantees of origin or sell the electricity with the Nordic residual energy mix. The purpose is for the customer to easily be able to see where the electricity comes from. In 2019 only 25 % of produced electricity was covered by guarantees of origin. The rest was covered by the residual mix, with an environmental impact of 338.53 g $CO_2$-eq/kWh.[63]

Sweden has a energy consumption mix of 52 g $CO_2$-eq/kWh. It is calculated based on the $CO_2$ emission intensity of different types of power plants over its entire life cycle. This includes construction of the plant, production of fuel, the actual energy production and dismantling of the plant.[64]

## 4.1 Delivery Quality and Reliability

Europe is connected through the power grid. Countries can supply others in times of high production, this contributes to lower the energy prices. In Sweden, high production happens in times of heavy rainfall and high winds. The renewable energy sources are unpredictable, and having a joint system a good source of a reliable power supply. Not all countries in Europe have a majority of renewable energy sources. This means that energy imported from other countries can have higher $CO_2$ emissions per kWh. Reliable power supply is prioritized over keeping emissions low for the electricity production.[65]

Both power reliability and energy reliability is important in a grid connection. The power reliability describes the system's ability to cover a instantaneous load and energy reliability is the system's ability to cover energy consumption. The main goal is for all users to have more than one supply line of power. Power demand varies both daily and seasonally with daily peaks in the mornings and early evenings, and seasonal peaks in the winter. This is seen in figures 4.2 and 4.3. During very cold and dry winter periods the energy reliability can be challenged. In this period the energy consumption is high and production is low due to weather.[65]

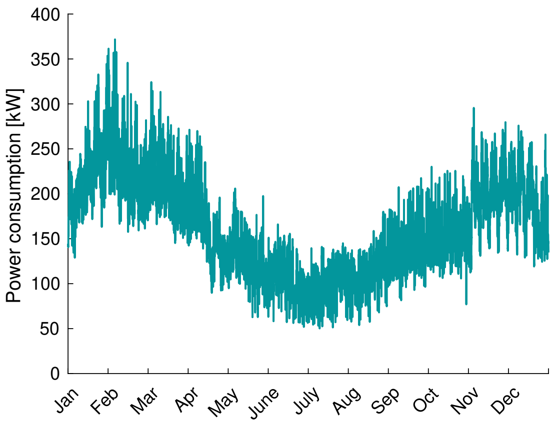


**Figure 4.2:** Monthly power consumption at Åre Östersund airport.[66]

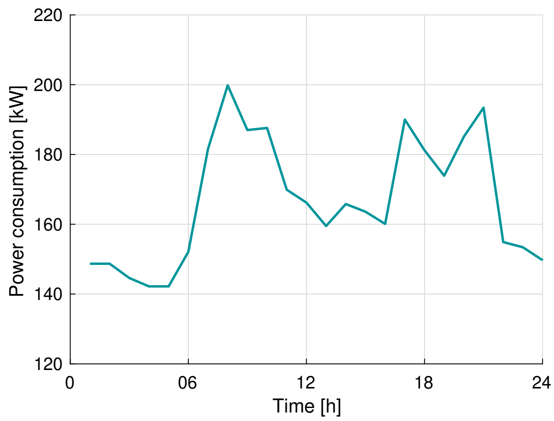


**Figure 4.3:** Daily power consumption at Åre Östersund airport.[66]

## 4.2 Grid Stability

An important characteristic for the grid is the frequency, which is 50 Hz ± 2% in Sweden. Wrong or unbalanced frequencies can damage equipment and cause blackouts, therefore the grid is always under surveillance. The frequency decreases when the consumption of active power is higher than the production. Active power is what is supplied to consumers. Reactive power is the part of the production that cannot be used by the consumers, but it is still important for the voltage quality. Ideal voltage quality is a 50 Hz sinus curve at the right amplitude and without interruptions.[67, 68]

The amount of reactive power in the system is used to regulate the voltage level. When connecting or disconnecting large components from the grid, reactive power can be added or removed to secure that the voltage stays at the right level. To avoid extensive changes in power and keep the voltage at the right level, users are given restrictions in power use from the power company. Voltage regulation becomes more important as more renewable sources with irregular production is connected to the grid.[67, 68]

Grids can be categorized as a stiff or weak grid. The difference is the short circuit performance, standard current is lower than the short circuit current. When the current increases from the standard, safety measures are in place to protect the system and disconnects the current. Weak grids are sensitive to load variations, and experience high voltage drops and losses. Stiff grid is not affected by this and have minimal voltage drops and losses.[55]

Power grids are dimensioned to fit the period with highest consumption. Large sudden changes in the load can cause a stiff grid to become weaker. This is an important factor that must be considered when adding high power components. To make a weak grid stiffer it is possible to increase the short circuit current. This can be done by decreasing the distance between the consumer and the transformer, increase the capacity of the transformer or increase the capacity of the supply wires.[55]

## 4.3 Power Tariffs and Peak Shaving

Electrification of the transport sector and energy efficiency are among important technologies in the green transition. Creating challenges for the traditional power grid construction with high peaks. A solution for facing this challenge is implementation of power tariffs. This type of tariff targets how grid fees are priced and aims to avoid high power peaks. The principle is to tax the part of the power consumption that exceeds a certain threshold.[69–71]

Normally grid fees are payed in terms of energy, but because of the extended peaks on the grid, power tariffs are considered. It is introduced to reduce power peaks with the help of price mechanisms. It is essential to create conditions for better and more efficient use of the grid, which in turn can delay cost-intensive investments. Power tariffs contribute to distribute the consumption over hours and days, so investments in new grid systems can be reduced or postponed. Local solar cell systems can be a contributor to avoid these additional fees by using a local renewable electricity source to shave peaks.[69–71]

Peak shaving is the process of reducing periods of high temporary loads on the power grid. This means highest power consumption as previously illustrated in figure 4.3, between 7 and 10, and 16 and 21 hours. The electricity price can be higher during peaks, so reducing consumption can reduce the power bill.[72]

By using energy storage, it is possible to utilize periods with low power demand to store energy in for instance batteries, hydrogen or pumped hydro power plants. This storage can be applied during peaks to reduce the overall energy need from the grid as illustrated in figure 4.4. These storage systems are also a good backup source in case of power failure.[72]

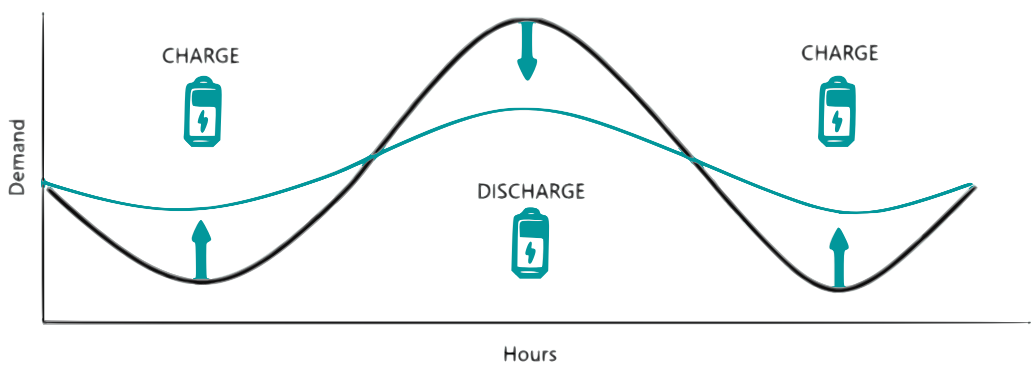


**Figure 4.4:** Battery contributing to peak shaving. Figure made based on theory.[72]

A method to reduce peaks is to increase the energy efficiency and optimize energy use. This means that the same process can be done with less power. The power system will experience large changes in the years to come due to climate policies and technical development. A common goal for European countries is to increase electrification. The consumption of electricity will therefore increase going forward. This contributes to pressure in the capacity of the grid and the need to utilize the power grid more efficiently.[60, 61]

Since 2017, NVE has worked on proposals of implementing power tariffs in the Norwegian grid fee system. The first proposal in 2017 presented drastic changes where customers decided their own power consumption limit. This proposal met large resistance in the power industry, who seeked a simpler model. NVE then worked on a new proposal presented in February 2020 which also met resistance and extensive protests. Today, NVE has discarded the proposal of power tariffs for private customers. The proposal increases the fixed costs, decreases the energy costs and implements power tariffs for businesses with an annual consumption over 100 MWh.[60, 73]

# 5 Battery Energy Storage

In the transition to a more sustainable society, batteries will play a huge part, especially as the electric automotive industry expands and energy storage becomes more essential. It is a flexible and diverse technology and have developed drastically in the last decades. There are currently multiple companies working on battery development and manufacturing, either announced or in operation. A map of companies in the Nordic can be found in figure 5.1.[4]

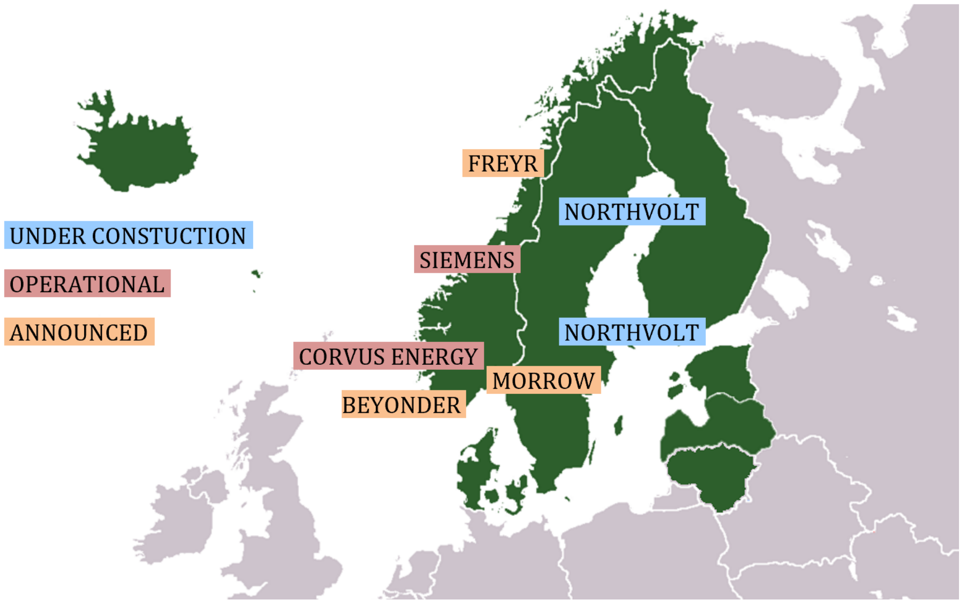


**Figure 5.1:** Announced and operational battery companies in the Nordic. Edited from original.[74]

Energy storage systems are important for maximizing energy efficiency. The extent of the maximizing is dependant on operation, size and placement in the network. It can contribute to peak shaving, enhance benefits from integration of renewables, aid power quality and reduce grid dependency. Batteries are widely used as energy storage, but other technologies include flywheels, $H_2$ fuel cells and various secondary batteries.[75]

## 5.1 Battery Technology

Batteries convert chemical energy to electric energy and can be divided into primary and secondary batteries. Primary batteries only undergo one cycle, and secondary batteries are rechargeable. This thesis focuses on secondary batteries, specifically lithium ion batteries, LiB. Batteries are made up of two electrodes, called anode and cathode, divided by an electrolyte. The cathode is positively charged, and the anode is negative.[76]

When discharging a battery an oxidation happens at one electrode and a reduction at the other. Discharging occurs when a load is connected to the battery. The number of electrons becomes excess at the anode where the oxidation happens, and the electrode is negatively charged. At the other electrode, the cathode, a reduction happens when it receives the excess electrons from the anode through the external load. At the anode, the positive ions from the oxidation reaction flows to the cathode through the electrolyte, and the negative ions from the reduction reaction in the cathode flow to the anode.[76]

When an external energy source is connected to the battery it will charge. The reduction will happen at the negative electrode, and it will receive electrons from the external source and restore to its previous state. At the positive electrode the electrons will be directed to the source, and an oxidation happens. The electrode is restored to its previous state. This means that the battery works as an electrolytic cell while charging, and a galvanic cell while discharging. The two electrodes are of different materials with different oxidation numbers. On one side the oxidation number increases, and on the other it decreases. [76]

## 5.2 Battery Specifications

To charge a battery a current is needed over time. The charging capacity of batteries are represented as current per mass of electrode material. The charging current is represented by the C-rate, where 1 C describes that charging time from 0 % to 100 % state of charge, SoC, is one hour. With a C-rate of 2 C it takes half an hour to fully charge the battery.[77, 78]

SoC is often referred to as a percentage of maximum capacity, and depth of discharge, DoD, shows the percentage of capacity that has been used. The SoC affects the efficiency of the charge acceptance of the battery, this is illustrated in figure 5.2. At full discharge the acceptance is quite low, while it stays on a high level in the middle, and decreases when approaching full charge. At a low SoC the discharge voltage drops due to internal resistance and the discharge power decreases.[78]

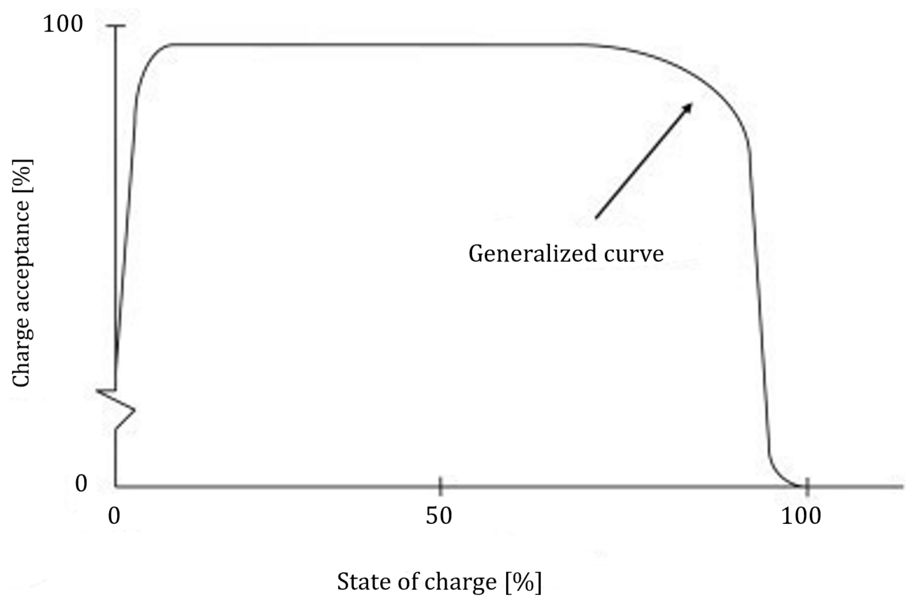


**Figure 5.2:** Generalized curve of effect of SoC upon charge acceptance.[78]

Equation 5.1 shows charging/discharging of a battery, where P is power fed to or from the battery in kW and E is actual energy capacity in kWh.[78]

$$SoC(t) = SoC(t_0) \pm \frac{1}{E} \int_0^t P(t) \tag{5.1}$$

The charge and discharge of a battery is called a cycle, and after a number of cycles the battery will lose capacity. The expression state of health, SoH, is used as a measure of the condition of the battery and is shown in equation 5.2 where L is number of cycles in a lifetime and $E_0$ is theoretical maximum capacity. To optimize the decrease rate, a standby SoC of 50 % is optimal. The health of a battery can also be described as in equation 5.3, as the relation between current maximum capacity and the theoretical maximum capacity.[78, 79]

$$SoH(t) = SoH(t_0) - \frac{1}{2 \cdot L \cdot E_0(0)} \int_0^t P(t) \tag{5.2}$$

$$SoH(t) = \frac{E(t)}{E_0} \tag{5.3}$$

A battery will reach end of life, EoL, often by default when SoH reaches 70–80 %, depending on the type. SoH is affected by the number of cycles, the charge and discharge C-rate, DoD, time, and change in temperature.[78]

SoH in a LiB is more likely to be lower with a high C-rate, and higher with a low C-rate. Some of the Li-ions will be immobilized with age, and as a result not accessible at higher currents. A SoC between 20 % and 90 % is recommended for LiB to slow the aging process. Figure 5.3 illustrates that cyclic lifetime before EoL is dependant of average depth of discharge of the battery. If the battery is completely discharged for every cycle, it reaches EoL after less than 5000 cycles.[76, 80]

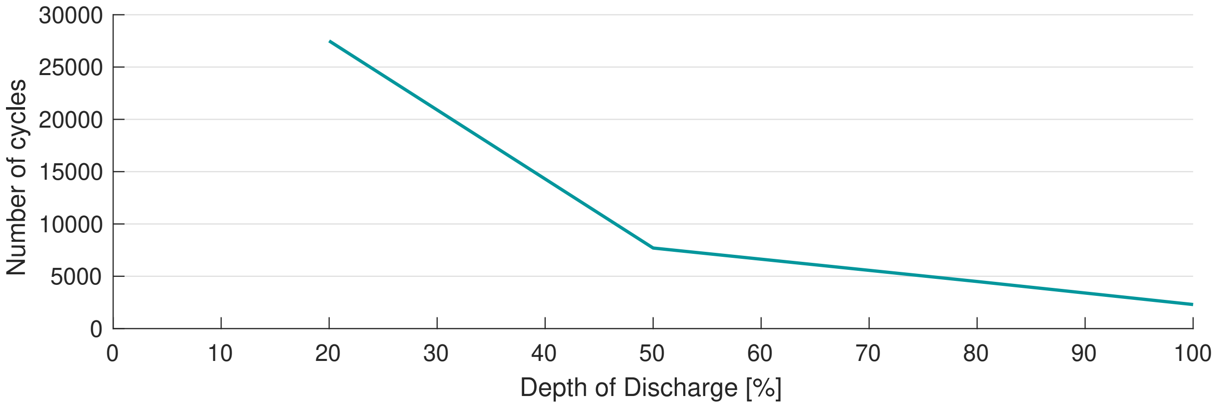


**Figure 5.3:** Cyclic lifetime as a function of average depth of discharge.[80]

## 5.3 Li-ion Batteries

LiB is made of lithium, which has a high standard reduction potential, resulting in LiB having a high power to weight ratio. These specifications make LiB one of the most common rechargeable batteries, seen in everyday life in most things from phones to EVs. The average cell voltage of LiB is 3.6 V. The lithium is combined with another material to make the chemical reaction.[76]

Charging of the battery happens when it is connected to an energy source. In LiB the lithium in the positive electrode gets ionized during charging. The electrons get pushed from the cathode to the anode through the external circuit. The ionized $Li^+$ ion moves to the anode from the cathode through the electrolyte. During discharging, the circuit is connected to a load, and the $Li^+$ ions and electrons moves back to the cathode, figure 5.4 illustrates this.[76]

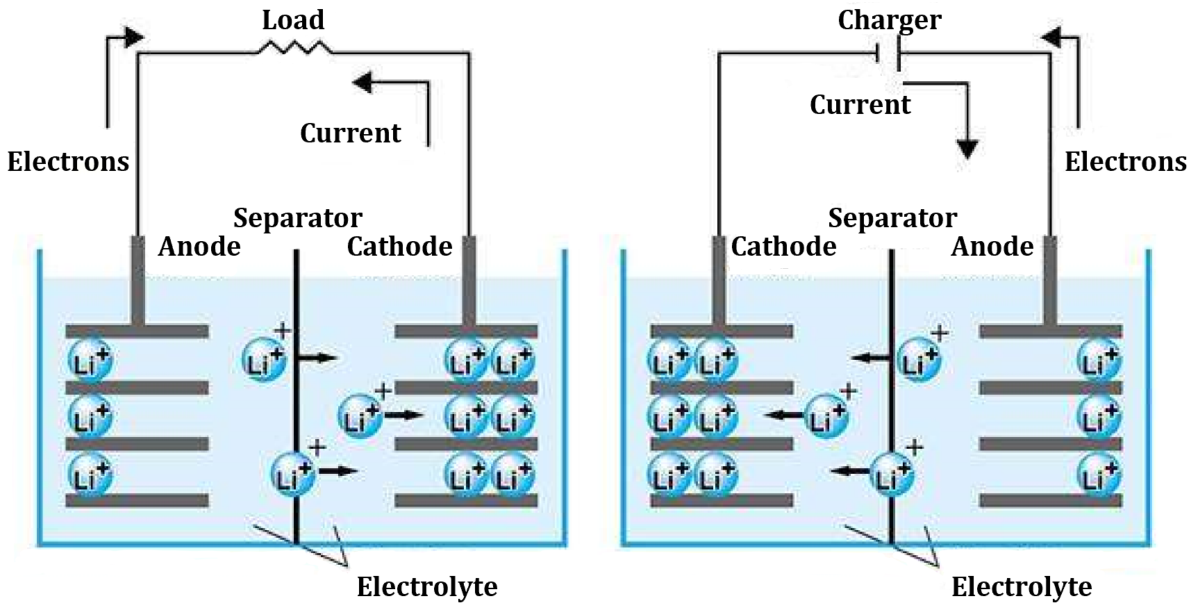


**Figure 5.4:** Movement of ions in charge and discharge reactions of a lithium-ion battery.[81]

### Cathode Materials of LiB

The cathode material of a LiB determines the battery performance. In large scale energy storage systems some of the most common materials are Nickel Manganese Cobalt NMC, Lithium Cobalt Oxide LCO, and Lithium Iron Phosphate LFP. The specific performance of the different cathode materials is shown in figures 5.5, 5.6 and 5.7.[82]

NMC has an overall good performance, especially in specific energy. This material is optimal for systems that need frequent cycling and a long lifetime. LFP batteries have a reduced specific energy, and higher self-discharge rate than other LiB compositions. This entails that LFP can become unbalanced with aging. Because of its high specific energy, the LCO is commonly used in mobile devices, but its short life span, high cost and lower performance makes it lose favor compared to other alternatives of ESS. The cathode materials consisting of cobalt are common in EV batteries, and the growing demand will surpass the supply.[82]

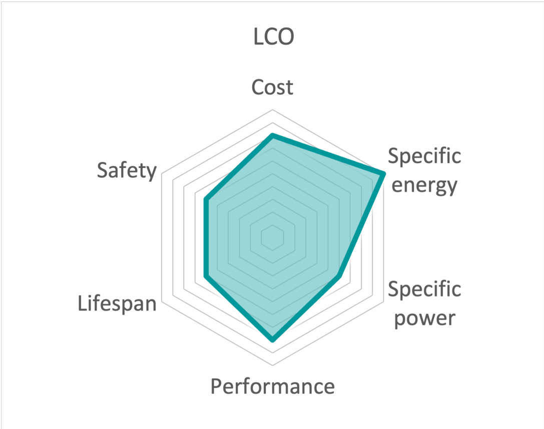


**Figure 5.5:** Performance of LCO.[82]

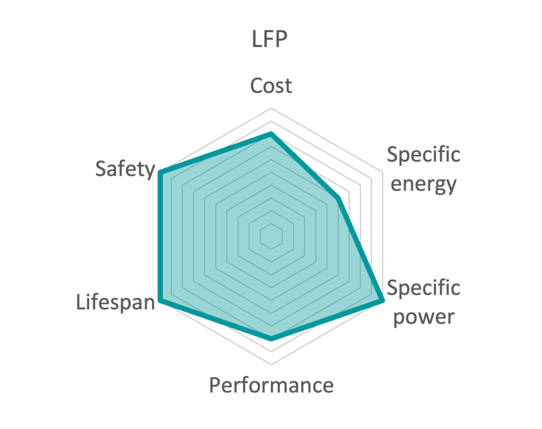


**Figure 5.6:** Performance of LFP.[82]

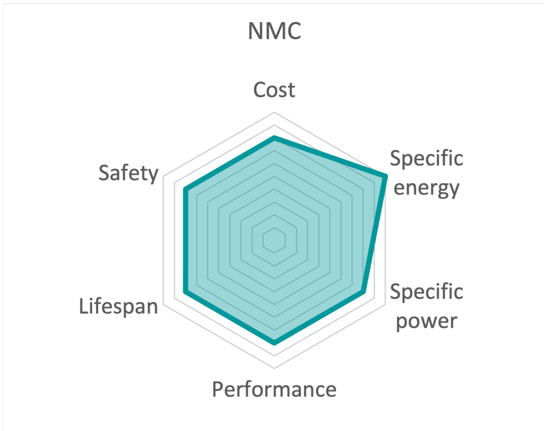


**Figure 5.7:** Performance of NMC.[82]

## 5.4 Safety Issues Batteries

There are taken many precautions to avoid malfunction of batteries. Extensive testing and analysis have gone into making LiB safer. Newer batteries will have a circuit breaker built in to react when the battery is done charging or get too hot. Most reported failures are from non-certified batteries or incorrect use. Incorrect use ranges from excessive vibration, use in improper heat, and charging below freezing.[83]

Fire safety following the increasing use of batteries due to electrification is an important factor to create a safe and stable transition. Large investments are being made in the battery industry and large factories are built worldwide. This upscaling leads to high demand for minerals, which makes recycling crucial. Malfunctioning of batteries that can lead to fire are also going through extensive testing and analysis to make batteries safer.[47]

The battery cell itself provides minimal risk of fire and is a small part of the battery system. The only flammable component in the cell is the electrolyte. Chance of fire in a LiB cell is 1 to 10 million. The risk scales with larger battery packs. The cell itself causes minimal risk, but mechanical, thermal and electric components are the most common source of fire. High voltage can cause strain on the battery cell.[84, 85]

Looking at the established technology for electric cars, a fire rarely occurs when charging. The only risk is if the battery is overloaded or if it does not fit optimally with the available equipment. Old or damaged cables can present a risk of fire.[84, 85]

When a battery is burning, gases are released. The most dangerous is hydrogen fluoride. It is highly corrosive and toxic, and can lead to blindness and worst case death. This is a large risk for the responders. A discussed method presented by Siemens is to install a gas detector that can discover fire at early stages and hopefully control it before a thermal rush and ignition. Water can be used as extinguisher, but it has disadvantages. Water can lead to substantial damage on various components and create a toxic chemical mixture in need of extensive environmental clean-up. Another alternative presented by Siemens is to release nitrogen when the detectors discover gases. The nitrogen can displace the oxygen, which will prevent ignition until emergency services arrive. This is still in the researching phase.[47, 85]

If a fire occurs in a battery, it must be placed in quarantine afterwards. It is important to pay attention to thermal variations within the battery and focus on cooling. This quarantine can be from hours to days dependent on the battery type.[47]

## 5.5 Batteries as Utility-Scale Energy Storage System

A battery cell is where the chemical component in a battery is stored. It is often cylindrical or prismatic shaped. The cells are further connected, in parallel or in series, to create the desired energy capacity and voltage of the battery. Serial connection results in an increase of voltage and parallel connection results in an increase of capacity. Multiple cells make up a module, where multiple modules again make up a battery pack. A battery pack describes the whole compartment in which the battery functions. It contains the battery cells, a control software, and a temperature management system.[86]

To control a battery module a battery management system, BMS, is used. The BMS is a intelligent system that monitors and manages the battery to optimize safety, performance, balancing and SoH. In addition, the BMS regulates the charging and discharging of the battery, thus protects the battery from overcharging, deep discharge, and charging too fast. The BMS plays an especially important role in large batteries with multiple cells, modules and components, where safety is important.[75]

Using batteries as energy storage systems, BESS, contributes to using energy more efficiently. With smart control a BESS can assist in peak shaving from the grid by charging and discharging at optimal times, regulate frequency and use voltage control. It can also make it more favorable to install and use renewable energy sources. In table 5.1 a comparison of characteristics in LiB, $H_2$ fuel cells and lead acid batteries LAB, is shown.[75]

**Table 5.1:** Comparison of different characteristics of three ESS technologies.[75]

| | **LiB** | **$H_2$ fuel cell** | **LAB** |
|---|---|---|---|
| Efficiency [%] | 85-90 | 25-58 | 70-90 |
| Response time | 20 ms | $< 1$ s | 5-10 ms |
| Lifetime [y] (cycles) | 5-15 (1000-20000) | 5-20 (1000-20000) | 3-15 & 2000 |
| Energy capital cost [$/kWh] | 600-3800 | 15 | 300-600 |
| Environmental impact | Moderate | Small | Moderate |
| Power quality | ✓ | ✓* | ✓ |
| Energy management | ✓ | x | ✓ |
| Renewable source integration | ✓ | ✓ | ✓ |
| Renewable energy backup | ✓ | x | ✓ |
| Emergency backup | ✓ | x | ✓ |

✓= proven, $x$ = promising but not proven , * As long as hydrogen is available

Some of the advantages for the LiB in BESS is the high density and efficiency, and also minimal self-discharge. One of the disadvantages is the EoL process, where the recycling of the raw materials is expensive. The advantages of the fuel cells are minimal self-discharge, possibility of long-term storage and availability of different cells for various applications. The main disadvantage is the repeated need for expensive catalyst. LAB have a low cost, however it also has a low energy density.[75]

The right selection of ESS for a microgrid is dependent on many factors, such as required capacity and performance, size, cost and available resources. The cost of lithium-ion battery packs, for both utility scale projects and EV, have declined drastically the last years, as illustrated in figure 5.8. The cost of battery packs in utility scale projects has decreased with 63 % in seven years.[87]

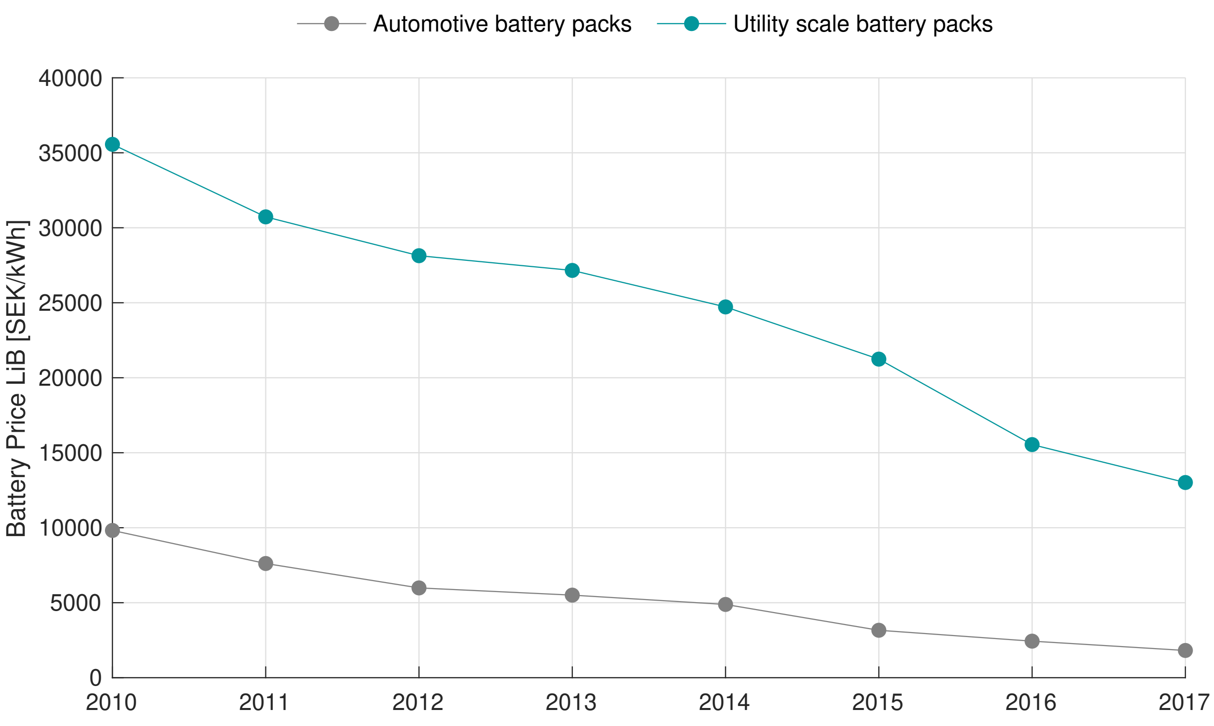


**Figure 5.8:** Evolution of Li-ion battery price from 2010 to 2017 for utility scale and automotive packs.[87]

# 6 Solar Cells

The sun is an eternal and renewable energy source that is important in the green transition. Solar power is one of the fastest growing technologies worldwide and can be utilized in several ways. Solar radiation can be converted to electricity via photovoltaic solar cells. Photovoltaic solar cells will be referred to as PV in this thesis. The electricity output from a PV is characterized by fluctuations and shows a daily and seasonal variability.[71]

PV electricity contributes to approximately 3% of the electricity supply in the global energy supply system. Electric current can be conducted in many ways dependent on material. Silicon modules, including poly-crystalline Si and mono-crystalline Si, account for 95 % of the global market share. Polycrystalline silicon PV have been dominant on the market for a long time but share the market with monocrystalline silicon PV today. Monocrystalline and polycrystalline silicon will respectively be referred to as mono-Si and poly-Si in this thesis. Mono-Si PV are single-crystal silicon PV and have grown a lot on the market the last years thanks to fast technology development and higher efficiencies. Mono-Si PV is the dominant technology with a market share of approximately 75 % in 2020.[88–90]

Average global price of a mono-Si PV module was 2.41 SEK/W in April 2021 and 16.9 SEK/W in 2010. This reduction of 85 % emphasizes the large market increase and technology development. The trend is illustrated in figure 6.1 alongside an increasing global annual PV module production. Module production in 2020 is affected by Covid-19, while module price and production in 2021 is based on predictions.[91–94]

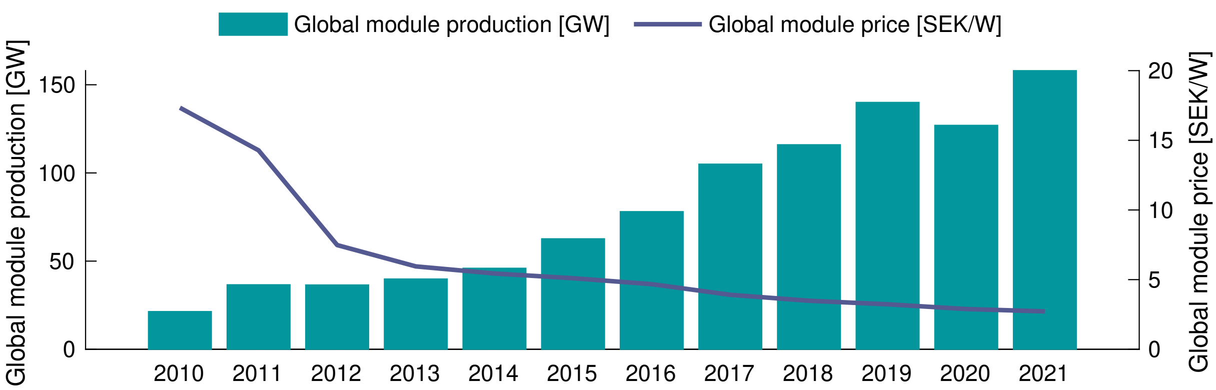


**Figure 6.1:** Development of global PV module price and production from 2010 to 2021.[91–94]

The installation costs are often lower per peak power for large commercial investments than smaller private installations. Various sources state a cost between 7 and 8.9 SEK/$W_P$ for commercial PV installations.[95, 96]

New technologies of installing PV are developing in the market. The future of PV will include PV tiles, transparent PVs resembling windows, concentrated PVs and bifacial PVs. Concentrated PVs use lenses or mirrors to concentrate the sunlight creating a larger efficiency. It is currently expensive because it requires extra components like solar trackers and cooling mechanisms. Bifacial PVs transform solar energy to electricity at both its top and bottom side and can deliver up to 50 % more than a conventional PV.[97, 98]

## 6.1 Construction of a Solar Power System

PV produce electricity through the photovoltaic effect. The principle is shown in figure 6.2 where solar energy is converted into an electron flow that generates electric power. It is normal to distinguish between good-, bad- and semiconductors. Semiconductors are the ones used in PV. By adding p-type and n-type dopants to semiconductors, the electric and conduction properties of the chemical material changes. The electron flow these dopants activates creates a higher energy state at the conduction band. Photons from solar radiation are absorbed and electrons are released. Electric current is a result of these electrons being captured.[99, 100]

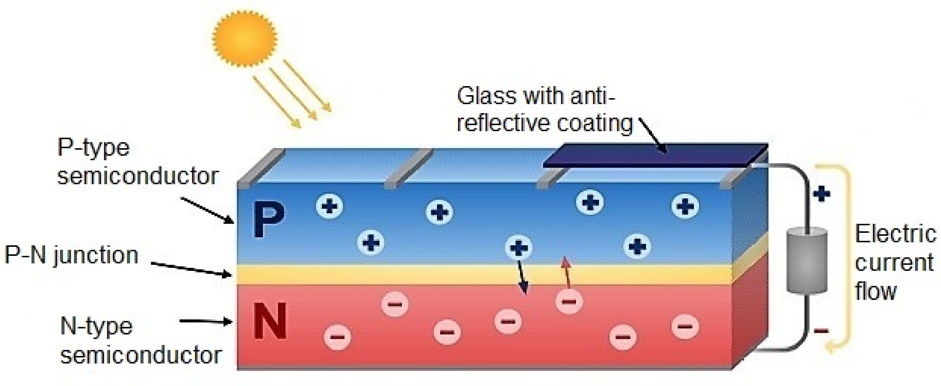


**Figure 6.2:** Electric current flow and semiconductors in a solar cell.[101]

The output of a PV cell is DC electricity. PVs are connected in series to increase voltage. The series of PVs are then connected in parallel to increase current output. Normally, between 20 and 60 cells are packed together and form a module under a transparent cover and a waterproof seal.[99]

Maximum power of a PV installation is referred to as peak power. It is calculated at AM1.5 corresponding to $\phi$ = 1000 W/$m^2$. AM is air mass and is the distance the sunlight must travel compared when the sun is directly over the panel. AM1.5 is often used as reference solar spectrum. Peak power of a single PV module is shown in equation 6.1. $P_{W_P}$ is peak power in W, A is area of the module in $m^2$, $\eta$ is efficiency and $\phi$ is irradiation in W/$m^2$.[99, 102]

$$P_{W_P} = \eta \cdot \phi \cdot A \tag{6.1}$$

The efficiency of a PV cell is the amount of electrical power converted in the cell, compared to the energy from the solar irradiation. Average efficiency range for a mono-Si PV cell is between 18 and 22 % in 2020, but it can theoretically reach a maximum efficiency of 33 %. The average efficiency for poly-Si PV cells is between 15 and 17 % in 2020. This development is happening fast and the efficiency is expected to further increase.[97, 103]

Poly-Si has an expected lifespan up to 25 years, while mono-Si have an expected lifespan of minimum 25 years. General silicon PV cells have a production degradation of 80 % after these years. The production degradation rate for mono-Si is approximately 0.5 % per year of the peak power for the entire installation.[99, 104, 105]

A PV system is built up of several different components illustrated in figure 6.3. The DC electricity produced by the PV panels are transformed into AC electricity using an inverter. The inverter also regulates the battery charge for systems with battery storage. The power from the inverter is then distributed to AC loads. The AC loads are appliances or components that consume the power generated by the PV. The PV system can also connect to the grid with the help of a meter, making it possible to sell excessive electricity. In addition to these main components, balance of systems, BOS, is important to optimize the system. BOS provides standard safety and interconnections in the PV system. It includes fuses, switches, properly sized cabling, circuit breakers and meters.[106]

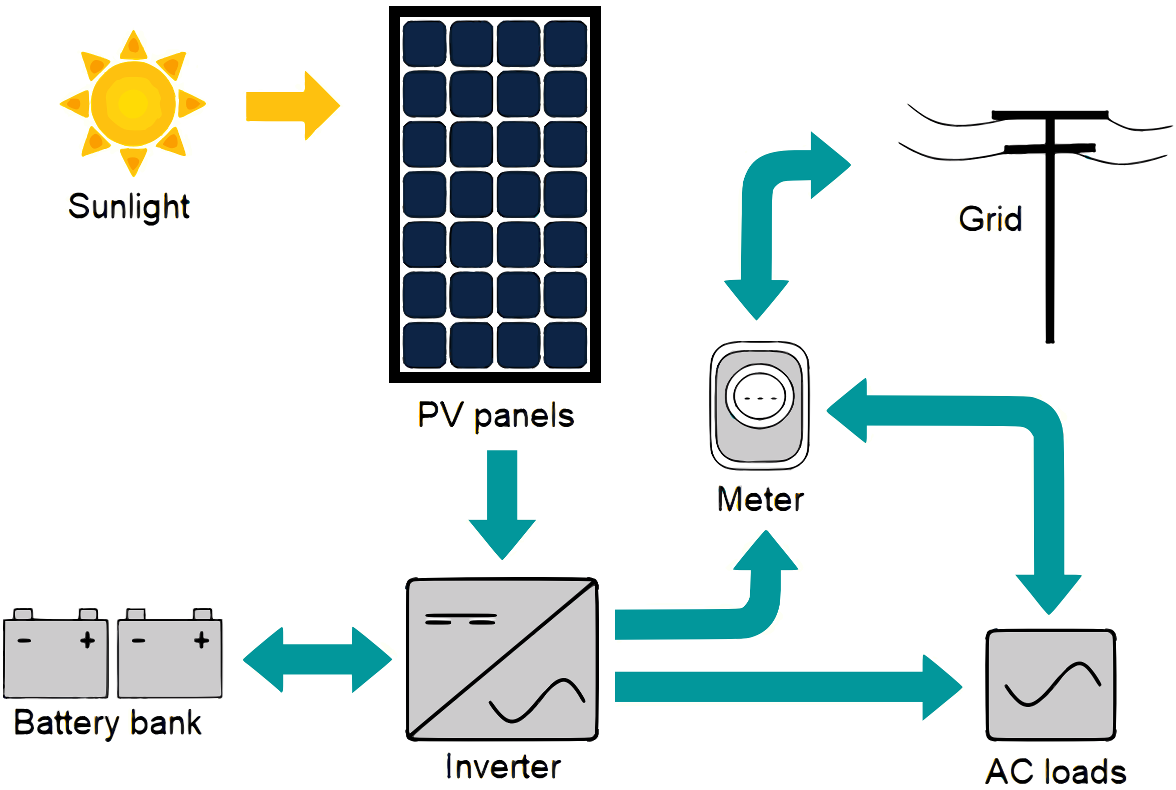


**Figure 6.3:** Components from production to utilization in a PV system.[107]

The incline angle of PV panels is important regarding the amount of solar energy the panels can utilize. The compass direction the sunlight is shining is called azimuth angle. This angle varies throughout the day and year and varies with latitude. Vertical direction is reference and it is closest to 0° in the middle of the day. In the northern hemisphere, a general rule is that PV should face south. This means PV incline should be more vertically mounted the further north the installation is. Optimal incline for a PV installation in Norway and Sweden is around 40°, depending on latitude.[99, 108, 109]

There are different installation options for PV panels, tiltable or fixed. Fixed PV should have a fixed angle that relates to the latitude of the location. Tiltable PV adjusts the angle of the PV in order to consistently track the sun throughout the day. A panel can track the sunlight with a single-axis tracker or a dual-axis tracker. The panel can either track in north-south direction, or both in north-south and east-west direction. Solar trackers are typically used for ground-mounted solar panels. The energy production is larger for tiltable PV installations. In addition to incline, the distance between the rows is important to avoid overshadowing by the modules.[99]

## 6.2 Solar Conditions in Östersund

Åre Östersund airport is located in the middle of Sweden at latitude 63° 11' 47" N and longitude 14° 29' 23" E. The climate in the area is characterized by cold winters with snowfall. Both snow cover, solar conditions and temperature must be considered when installing PV in this area.[110]

Sweden's third largest solar park is located in Östersund. It is operated by Jämtkraft and the latest PV cell technology is used. The PVs at Östersund Solar Park has an efficiency of 19 % and a life expectancy of 30 years. Energy payback time, EPBT, is between 1 and 1.5 years. The type used is GCL Monocrystalline silicon. Each panel is 1640 x 992 x 35 mm large and weighs 18 kg. The park consists of almost 10 000 PV cells with maximum production of 3 MW. The solar park in Östersund is shown in figure 6.4.[88, 111]

**Figure 6.4:** Östersund solar park. 10 000 panels with 3 MW peak power.[88]

Generally, the efficiency of a PV is higher at cold temperatures. Electrons are more active at higher temperatures, which cause higher leakage of internal energy. Lower temperatures will consequently have less leakage, higher voltage and higher efficiency. Despite this, one cannot guarantee substantial production in the winter climate. Low solar radiation leads to less energy that can be utilized by the PV panels.[71]

Solar power is only available if sunlight hits the PV surface. This means there is little to no production at night or when the cloud cover is thick. The winter is also affected by snow and low radiation angle. Snowfall can have both positive and negative effects. The production can increase as a result of reflection from the surroundings, especially snow-covered surfaces. This is called the albedo effect and increases the amount of electricity produced, as long as the panels are free from snow.[71]

Swedish Meteorological and Hydrological Institute has published an overview of snow depth and ground conditions in Östersund. The average snow period with significant depth of snow is from December to mid-March. Snow can reduce the production if covering the panels. The impact is dependent on the tilt angle, where a larger tilt angle is less affected by snow. The sun also contributes to melting snow off the modules. Average reduction caused by snow is 10 % of total production according to a research done on how various factors affect PV performance.[112, 113]

## 6.3 Solar Cell Safety Issues

If installing PV at or near an airport, several safety and production aspects must be considered. This includes the possibility for reflections from the panels, electro-magnetic interference EMI on airport technology and the placement of the PV structure. A complication when installing PV at airports is a national interest issue. The Swedish Armed Forces and the Swedish Civil Aviation Administration can have interventions when applying for a license. The Swedish Armed Forces have on other occasions opposed to installations of PV fearing it might disrupt vital security systems.[27, 114, 115]

### Solar Reflection

Even though most PV use anti-reflection coating made of Silicon Nitride SiNx, the surface of PV modules can still reflect light. This reflection is a safety concern because it can cause flash blindness, which is a brief loss of vision, for pilots during final approach. A study published by Federal Aviation Administration in 2015 gives insight on how reflection from PV modules affects aviation. Results state that impact of reflection can be reduced if the angle of the reflection is larger than 25° from the direction the pilot is facing. Therefore, the study recommends that the installation of PV at airports is placed over 25° from the direction of final approach to ensure that pilots does not face reflection when landing.[115, 116]

### Electro-Magnetic Interference

EMI is radio frequency emissions from PV systems. It can interfere with nearby radio receivers, as well as communication devices, navigational aids and explosive triggers. The risk of interference is low, but it is important to evaluate. The PV panels does not emit EMI themselves. The inverter is the only component that may emit EMI from a PV system. This component produces very low frequency EMI, below background levels at a distance above 46 m. The risk of EMI can be reduced by good enclosure grounding, filtering and circuit layout of the inverter. The risk is also dependant on frequency. EMI is not expected over 1 MHz because inverters have low frequency operations. The risk is also minimal at lower frequencies due to limiting signal propagation.[117]

### Placement of Solar Cells

PV is a modular construction that can be adapted into existing landscape without major modifications. However, no physical structure is allowed to be installed in a way that can lead to safety issues at airports. The most suitable PV installation solutions at airports are roof-mounted or ground-mounted systems as illustrated in figure 6.5 and 6.6.[118]

**Figure 6.5:** Roof-mounted solar cells.[119]

**Figure 6.6:** Ground-mounted solar cells.[120]

Roof-mounted systems avoids unnecessary encroachments in nature, as well as extra costs that may come with processing landscapes. It can have the benefit of unobstructed solar exposure and can often be mounted directly on the roof without a lot of preparation. The incline of the roof must be evaluated and a flat roof needs more support than an inclined roof. The existing roof loading capacity must be analyzed to determine if structural reinforcements are required and how much it will impact installation cost. The size of the installation is important when considering roof-mounted or ground-mounted systems.[118]

Ground-mounted systems require a relatively flat terrain to avoid extra ground processing costs. In order to confirm the long-term stability of the soil, geotechnical analysis is necessary. Ground-mounted systems need extra support of poles and steel beams to avoid destabilization. The panel-for-panel cost is therefore often higher for ground-mounted systems than roof-mounted systems. It can be economically beneficial to install PV on the ground if the scale of the project is large enough and space is not a limiting financial consideration.[118]

# 7 Hydrogen and Fuel Cells

Hydrogen as a energy carrier is a flexible way to store energy. It is the most similar storage method to diesel and gasoline, explaining why this field receives so much attention. The main advantage of hydrogen is that the only product of the combustion is $H_2O$, seen in equation 7.1. Ideal production and use of hydrogen is a closed chemical cycle, where the chemical compounds are neither created nor destroyed. Though this is not always the case today.[121, 122]

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) + energy \tag{7.1}$$

Hydrogen has obtained a bad reputation of being a highly flammable substance. Though it is a flammable substance, it is not more dangerous than other fuels if it is stored correctly. As seen in table 7.1, the auto-ignition temperature and detonation limit are higher for hydrogen than gasoline. The minimum energy for ignition in air is lower for hydrogen than gasoline. An important point to note is that in a fuel leak hydrogen would rise to the sky, while gasoline would spread around on the ground and increase the explosion risk.[123]

**Table 7.1:** Characteristics of hydrogen and gasoline.[123]

| Characteristics | | Hydrogen | Gasoline |
|---|---|---|---|
| Auto-ignition temperature | [°C] | 585 | 228–471 |
| Detonation limit in air | [% vol] | 18.3–59.0 | 1.1–3.3 |
| Min. energy for ignition in air | [MJ] | 0.02 | 0.24 |

## 7.1 Hydrogen Production

Hydrogen does not occur alone in pure state, and it has to be separated from other elements. Hydrogen can be produced from four main sources, natural gas, oil, coal and electrolysis.[124]

### Steam Reforming

Methane and steam react under high pressure and temperature, creating hydrogen and carbon dioxide. Equation 7.2 shows steam reformation, and equation 7.3 shows the water-gas shift reaction. This is the most used method of hydrogen production. The amount of emissions from the reaction is affected by how the $CO_2$ is processed. If the $CO_2$ is captured and stored, the hydrogen is referred to as blue hydrogen.[125]

$$CH_4 + H_2O \rightleftharpoons 3H_2 + CO \tag{7.2}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{7.3}$$

### Water Electrolysis

Water electrolysis is done by splitting water into hydrogen and oxygen, as seen in equation 7.4. This is the opposite reaction to the combustion of hydrogen in equation 7.1.[76]

$$H_2O(l) + energy \rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{7.4}$$

Today only 4 % of produced hydrogen comes from water electrolysis, and it is calculated to be 2.5 to 3 times as expensive as steam reformation. Electrolysis is more financially profitable as more hydrogen is produced, this can be seen in table 7.2. The table illustrates three power sizes of electrolysers, referred to as A, B and C. Indicating that small electrolysers are not a good financial investment if investment cost is compared to hydrogen production. If the electricity used in the electrolysis process is from renewable sources it is called green hydrogen.[126, 127]

**Table 7.2:** Characteristics of hydrogen production from electrolysis for different size electrolysers.[127]

| Electrolysers properties | | A | B | C |
|---|---|---|---|---|
| Electrolysers power | [MW] | 5 | 20 | 150 |
| Investment cost | [MSEK/MW] | 26 | 22 | 20 |
| Hydrogen production | [Tonne/yr] | 438 | 1752 | 13 140 |

## 7.2 Hydrogen Storage

The easiest way to store hydrogen is in gas form. Because of the low density, hydrogen in gas form is usually compresses and stored at pressures of 350 or 700 bar. This requires high pressure storage, which is comprehensive and expensive. For portable storage, weight and volume is the biggest issue. While for stationary storage, this is not as significant and the price of materials is more important. Extensive research is done today on different materials to make hydrogen storage more efficient.[128, 129]

Hydrogen can also be stored in liquid form, this requires a temperature of $-253$°C if stored at 1 atm. It is very important that the tanks are fully isolated to maintain the low temperature. This is both a expensive and technical process. New technologies leading to minimal boil off is being developed and will be very important to minimize losses and secure long term storage. Both these methods, and many others are constantly being researched. As further development is completed, the technology will mature and become more applicable in bigger energy systems.[129–131]

### 7.3 Fuel Cells

Fuel cells are used to convert chemical energy to electrical energy, and a variety of fuel cells have been developed the last century. The alkaline fuel cell is the most developed and mature technology, and cost of manufacturing is low. The Proton Exchange Membrane Fuel Cell, PEM, is a newer technology, with currently higher manufacturing costs. Advantages with PEM is simple maintenance, fast start-up and no corrosion.[132]

$$Cathode : O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{7.5}$$

$$Anode : 2H_2 \rightarrow 4H^+ + 4e^- \tag{7.6}$$

A fuel cell can be compared to a battery during discharging and consists of a cathode and an anode. Respectively equations 7.5 and 7.6 shows their chemical reactions. Electrons travel from the anode through an electric circuit creating power, to the cathode. Figure 7.1 shows this graphically. One cell operates at voltage of between 0.5–0.8 V, and many cells are combined in a stack to create a fuel cell with a high enough voltage.[76, 124]

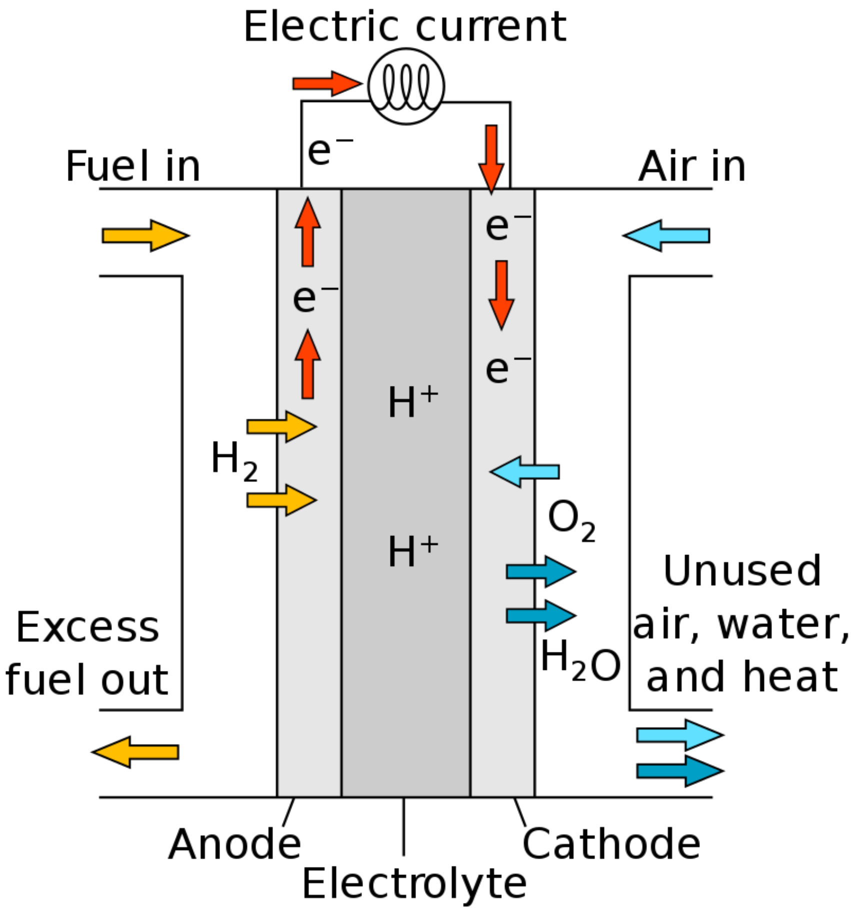


**Figure 7.1:** Movement of ions in a fuel cell creating electricity.[133]

## 7.4 Hydrogen in Östersund

The local power company in Östersund, Jämtkraft, has a road map for the future of hydrogen in the area. The plan consists of building an electrolysis plant in an industry area in Östersund, in vicinity to a combined heat and power plant, CHP. The CHP is seen in figure 7.2. The benefit of this location is the ability to produce Biojet. Biojet is a type of e-fuel consisting of a combination of $CO_2$ and $H_2$. Made from the $CO_2$ emissions from the CHP. E-fuels can be used as a fuel in planes to meet the $CO_2$ reduction demands from the Swedish government. The electrolysis process requires electricity, and the local electricity has a high percentage of renewable energy sources. This results in low emissions from the hydrogen production.[127, 134, 135]

In addition to production of Biojet, the hydrogen is planned to be used as backup for the power grid in times of low production from renewable sources. It can also supply other hydrogen users, for example vehicles. This includes transport to Åre Östersund airport for hydrogen-powered planes in the future. The local railroad can transport the hydrogen over long distances. Having a diverse market for hydrogen is important, as the investment cost is lower for a higher amount of hydrogen produced, as previously seen in table 7.2.[127, 136]

**Figure 7.2:** Östersund combined heat and power plant in vicinity to the planned electrolyser.[137]

# 8 Life Cycle Assessment

Life cycle assessment, LCA, is a method used to assess the environmental impacts of a product, process, or system over its life cycle. It identifies and quantifies the environmental burden of different technologies. LCA is often used to compare different products against each other to improve the impact of product and processes. The environmental impacts are evaluated differently in various assessments using a number of assessment methods. One of the most common is carbon footprint. Carbon footprint is the $CO_2$-equivalent emissions in the entire life cycle of a product. LCA is used in many industries to promote the sustainability of the product or firm in a competitive perspective.[138, 139]

There are four stages in a LCA, illustrated in figure 8.1. Stage one is to restrict the factors that are included in the assessment to better compare one product to another. Stage two is an analysis of the raw materials used to manufacture the product and their impact on the environment, as well as the system energy flow. Stage three is impact assessment where the inventory is categorized and the results of impacts are implemented. Lastly, stage four is a review of the results with data sensitivity and critical inspection.[138]

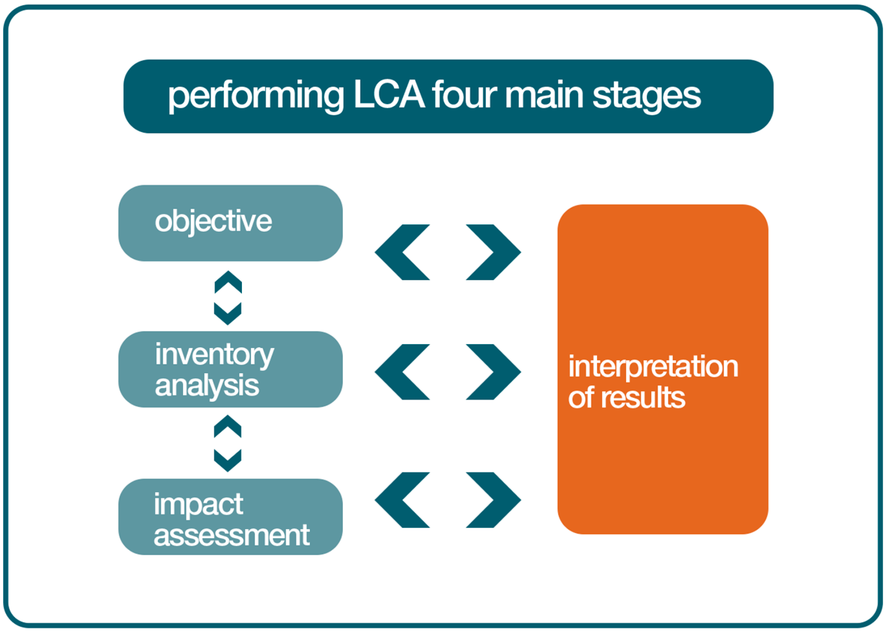


**Figure 8.1:** The four main stages of a life cycle assessment.[140]

The life cycle of a product can be divided into five phases. The first phase calculates the impact of the raw material used to make the product. The second phase is the manufacturing of the product. The emissions from phase two are closely related to the energy mix of the electricity and fuel consumption. Phase three is distribution and often refers to the relocation of the product. The fourth phase is the use-phase of the product. The length of the use-phase is dependent on operation and maintenance of the product. The final phase describes what happens when the use-phase is over and whether the product will be disposed of, reused, or recycled.[139]

## 8.1 Lithium-Ion Batteries

LCA of batteries are commonly divided into three phases, cradle to gate, use-phase, and EoL, illustrated in figure 8.2. The literature on this subject is often based on a variety of methods and limitations and is consequently complicated to compare with each other.[141]

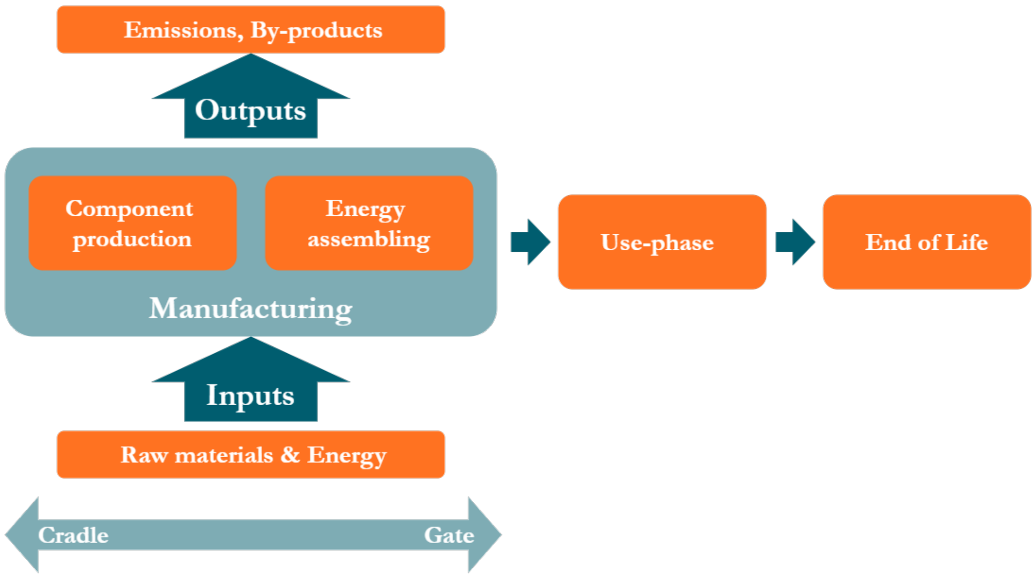


**Figure 8.2:** Stages of life cycle assessment in a battery energy storage system. Edited from origianl.[141]

The emissions from cradle to gate, also known as the production phase, are based on a number of factors. The different chemical compositions of the LiB results in dissimilar impact in an LCA analysis because of different raw materials. NMC is found to have a carbon footprint of 73 kg $CO_2$-eq/kWh in an analysis from the US, with materials from China.[142, 143]

The use-phase of the LCA is dominated by two factors, round trip efficiency losses and changes in unit dispatch. A number of studies have concluded that the use-phase dominates the LCA, with some indicating that up to 60–95 % of impact are a result of use-phase. The studies comparing LCA of different batteries as functions of mass or capacity could therefore be misleading. The use-phase impacts are also influenced by the energy mix of the location.[144]

EoL impact is calculated for different pathways, including re-use or repurposing, material recovery, and disposal. When analyzing LCA of grid-scale stationary BESS, there are a limited number of literature that include EoL. Currently, most existing systems were installed the last 5 years, and the concern of what to do with the LiB at EoL is not yet standardized. Current recycling rates for LiBs in general are around 3 %. Several startups founded in the last years, including Northvolt, are working on increasing this percentage. Northvolt aims to have 50 % recycled material in new cells by 2030.[22, 145]

In Norway, batteries of all categories can be sent to a company called Batteriretur to be handled. The approved service is capable of receiving all types and quantities of batteries through cooperation and partnership with other companies. The network ensures synergy gains for safety and the environment. In Sweden, the company El-Kretsen, accepts and recycles batteries throughout the whole country. They guarantee safe, efficient and sustainable handling of batteries and are focused on closing the loop.[146, 147]

## 8.2 Monocrystalline Silicon Solar Cell

In order to complete a LCA for mono-Si PV, both input and output factors from the production phase and further process steps are needed. Input factors can be the energy mix in the different stages and the processed materials. Output factors include the product itself, waste and emissions to air and water. Transportation method and distance must also be considered, as well as the processing needed on the chosen installation area.[71, 148]

GHG emissions in the operating phase is minimal for a PV system and can often be neglected. In the production phase, chemicals are used to produce the panels. PV manufacturers are working to cut production emissions and handle the chemicals used in production responsibly, but PVs are still associated with some chemical emissions.[149]

Carbon footprint and energy payback time, EPBT, are often used as PV LCA indicators. EPBT is the time required for an energy producing system or device to produce the same amount of energy that was used during manufacturing. EPBT is dependant on geographical location. PV systems in Northern Europe often have a EPBT around 1.5 years, while installations in Southern Europe can balance the input energy after 1 year or less.[149]

All components in a PV system have to be analyzed and included in carbon footprint and EPBT to get a representative result. The influence of Si-material, production and BOS is illustrated in figure 8.3 and 8.4. The efficiency of the mono-Si PV from 2013 is 14.8 % and the assessment is researched on a panel in France. The mono-Si PV from 2020 has an efficiency of 22.5 % and is researched in China.[90, 148]

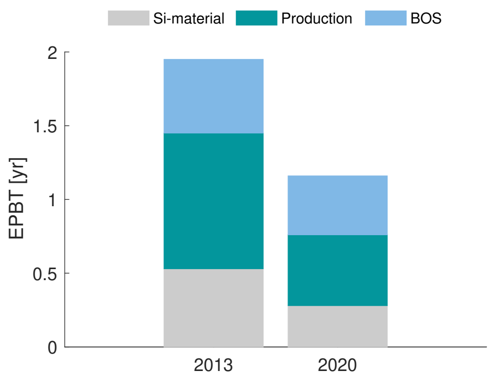


**Figure 8.3:** EPBT for mono-Si PV from 2013 and 2020.[148, 149]

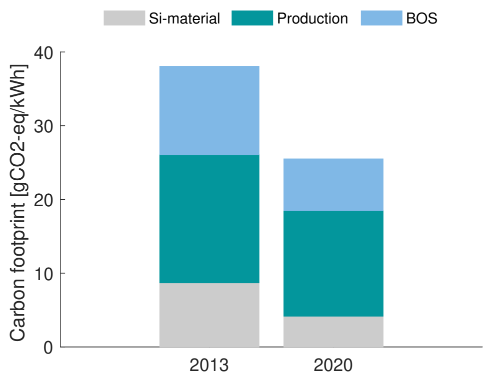


**Figure 8.4:** Carbon footprint for mono-Si PV from 2013 and 2020.[90, 148]

Figure 8.3 shows the EPBT of mono-Si PV from 2013 and 2020 and clearly illustrated a declining trend and that the production phase requires most energy. In 2013 EPBT for the PV system was 1.96 years and the material and production was responsible for 74 % of total EPBT. In 2020 EPBT for the PV system was 1.16 years and the material and production was responsible for 66 %. This shows a total EPBT reduction from 2013 to 2020 of 41 %.[148, 149]

Carbon footprint for a mono-Si PV system from 2013 and 2020 is illustrated in figure 8.4. Carbon footprint of mono-Si PV in 2013 is 38.1 g $CO_2$-eq/kWh, where material and production was responsible for 69 %. In 2020 carbon footprint is 25.6 g $CO_2$-eq/kWh and material and production was responsible for 73 %. Carbon footprint for mono-Si PV has been reduced with 33 % from 2013 to 2020. Values concerning both EPBT and carbon footprint underlines theory stating the production phase has the largest GHG emissions in a PVs lifetime.[90, 148]

A PV system needs minimal maintenance during operating phase. Typical maintenance is cleaning the panel surface if there is significant dust or snow on it. Other than this, a large PV installation needs regular service maintenance annually or every other year. The electric components external to the actual PV module are the components that typically needs to be replaced first.[108, 150]

Because of the descending price per panel, the demand for panels increases. This leads to more panels in rotation and requires a good system for recycling. A high degree of recycling minimizes the life cycle impacts of the panels. EU´s WEEE directive states that by 2018 85 % of PV waste must be recovered and 80 % recycled and reused. This requires all panel producers to finance the cost of collecting and recycling of PVs at EoL. Though recycling has environmental impacts, the advantages outweigh the disadvantages.[148, 151]

# 9 System Description

This chapter describes the main components of the microgrid, and the software and simulation methods used to simulate the energy system at Åre Östersund airport. The simulation software MATLAB and PSS DE®from Siemens was used to make the simulations of the energy system.

The simulation aims to make an efficient energy system, and facilitate charging of electric planes. Figure 9.1 shows the key components in the system. The most important part is how the grid in collaboration with a BESS and PV can cover charging demand from the planes, without compromising the airport overall demand. In addition diesel powered emergency supply generators are removed, and replaced by a sustainable solution.

The simulation is based on the components within the simulation boundary in figure 9.1. The airport load consists of current buildings and infrastructure with local power demand. Batteries are installed as energy storage and emergency power supply. Charging of electric planes is implemented in the simulation and charging of other electric vehicles is discussed as further work. Point of common coupling, PCC, describes the connection to external grid. The solar panels are included in the simulation as local energy production, and hydrogen production and storage is discussed as further work. The components work together as a microgrid, where the microgrid controller optimizes operations.

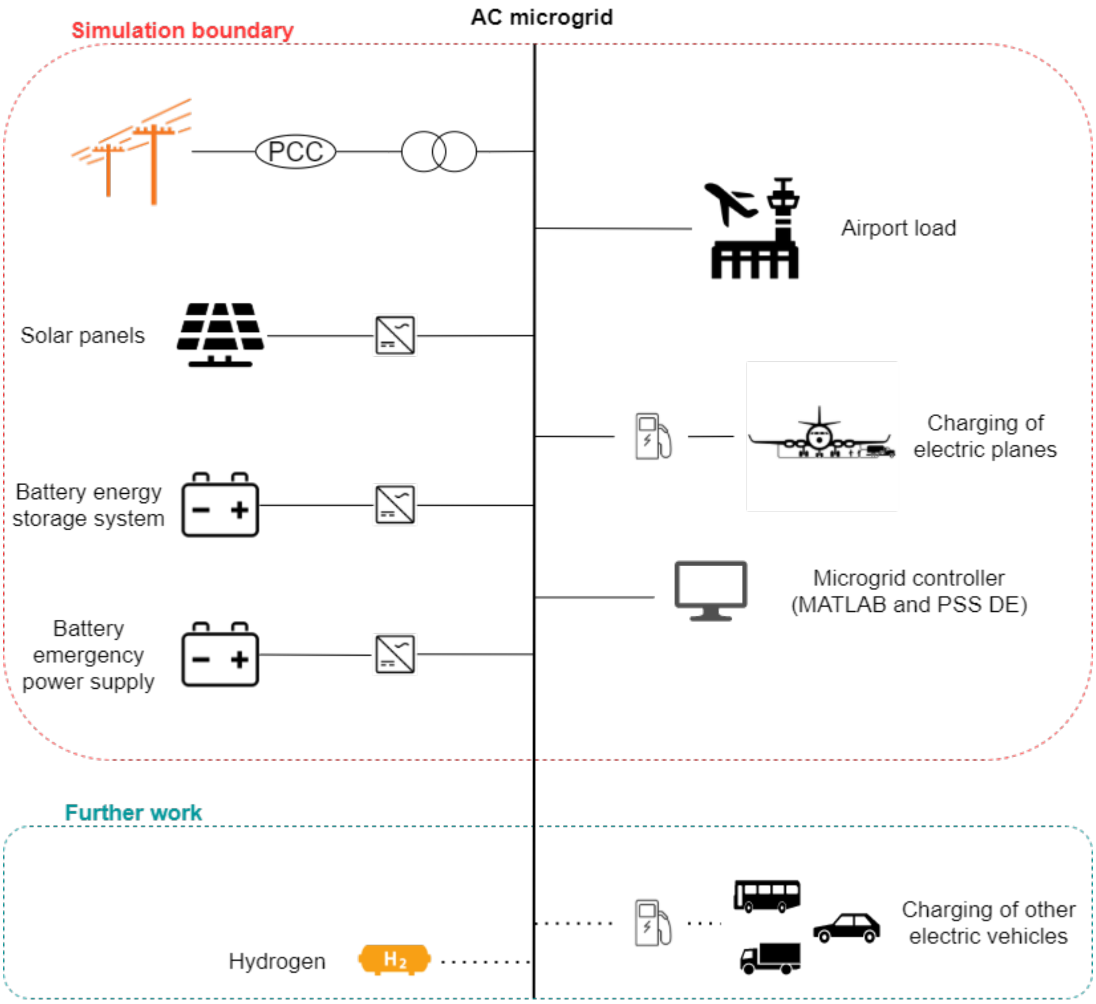


**Figure 9.1:** Schematic diagram of the simulated microgrid system and components in further work.

## 9.1 Project Timeline

A timeline with three steps have been developed according to future development in the aviation industry, where each represents a different time period in the commercialization of electric planes. Each step has a duration of five years. In reality, time between steps can be longer or shorter depending on the speed of the development.

For the simulation it is important to know how many planes require charging per day, and what speed the charging needs to be. This is a field in rapid development, so making precise predictions is very hard. Approximate flight patterns have been chosen for each step after conversations with the leaders of the Green Flyway project [27]. Following is a description of each step, with number of flights and speed of charging. Figure 9.2 shows the timeline for the simulation, with the added components at each step.

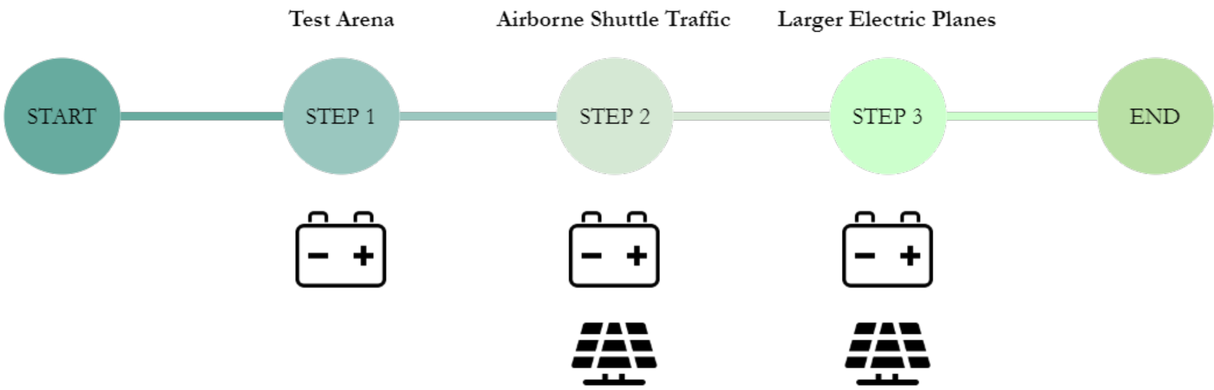


**Figure 9.2:** Simulation timeline with steps in the project with batteries and solar cells.

Step 1 is Åre Östersund as a test arena for emission free aviation. This step is mostly smaller planes like Phinix and Pipistrel, with a few ES-19 planes. Realistically there will be no set flight patterns in this period, as this is the testing phase. But a charging sequence had to be set in order to simulate. It will be important to test both slow and fast charging, to see what the planes tolerate in a testing phase.

In step 2 ES-19, is used as part of the public transport system with scheduled departures. Unlike the test arena, commercial operation has a greater demand for accuracy in departure time. This requires more fast charging, which can be challenging for the energy system. Step 3 is a continuation of step 2, with the addition of larger electric planes. This pattern is a even bigger challenge for the energy system, as chargers of up to 4 MW are used on the biggest electric planes.

### Step 1 Test Arena

Step 1 is Åre Östersund airport as a test arena for emission free aviation. Small two seat test planes and ES-19 are tested at the airport. Three to four small planes and two ES-19 planes need to be charged per day. The charger used for small planes is 12.8 kW. Chargers used on ES-19 vary from 175 kW overnight, to 1 MW fast charging. Table 9.1 shows an overview of type of plane, number of planes needing to charge and speed.[27]

**Table 9.1:** Number of planes per day in step 1. Charging varies between fast and slow speed.[27]

| Type | Number | Charger size [kW] |
|---|---|---|
| Small test planes | 3-4 | 12.8 |
| Heart Aerospace' ES-19 | 2 | 1000, 350 or 175 |

### Step 2 Airborne Shuttle Traffic

In this step Heart Aerospace's ES-19 is used in airborne shuttle traffic. Eight planes are charged on the weekdays, and four on the weekends. Similar chargers as in step 1 are used to charge ES-19 in step 2. The chargers vary from 175 kW overnight, to 1 MW fast charging. This charging sequence sets strict requirements for accuracy as planes need to be ready quickly. About half of the charging cycles a day are 1 MW, and the rest varies in lower speeds. Table 9.2 shows an overview of this.[27]

**Table 9.2:** Number of planes per day in step 2. Charging varies between fast and slow speed.[27]

| Type | Number | Charger size [kW] |
|---|---|---|
| ES-19 weekdays | 8 | 1000, 350 or 175 |
| ES-19 weekend | 4 | 1000, 350 or 175 |

### Step 3 Larger Electric Planes

Step 3 has the same flight pattern for ES-19 as step 2, with the addition of two to three longer distance planes per day. This can be seen in table 9.3. The larger planes are predicted to have an even higher charging demand using chargers up to 4 MW. The 4 MW charger is among the largest chargers currently under development.[27]

**Table 9.3:** Number of planes per day in step 3. Charging varies between fast and slow speed.[27]

| Type | Number | Charger size [kW] |
|---|---|---|
| ES-19 weekdays | 6 | 1000, 350 or 175 |
| ES-19 weekend | 3 | 1000, 350 or 175 |
| Larger plane weekdays | 3 | 4000, 3000 or 2000 |
| Larger plane weekend | 2 | 4000, 3000 or 2000 |

## 9.2 Key Components

In the following chapter the main components in the energy system are described and dimensioned. All components described are used as inputs in the simulation. The energy system in the simulation works as a microgrid, where in MATLAB the optimization is done manually and in PSS its done by a microgrid controller. Batteries are a crucial part of the energy system and works as energy storage. Energy systems are dependant on energy storage if grid capacity is not adequate. A PV installation is implemented to have local energy production and to assess how it benefits the energy system. There is a risk that PV installation at the airport can be rejected due to national interest issues, which is important to consider. Therefore simulations were done with and without PV.

### 9.2.1 Batteries

Batteries are going to be used as a energy storage system in the simulation. The Northvolt Voltpack Mobile System, hereby referred to as Voltpack, has been suggested to be used at the airport, and can be seen in figure 9.3. Therefore this is the battery used in the simulation.

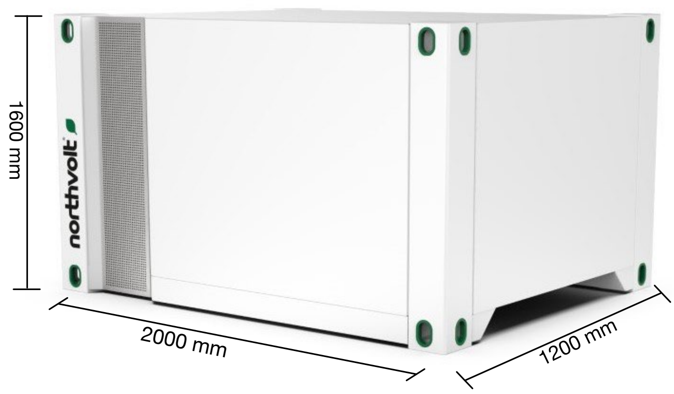


**Figure 9.3:** Dimensions of the Northvolt Voltpack Mobile System.[152]

The Voltpack is a versatile energy storage solution first presented in May of 2020 based on NMC technology. The solution is visioned to be an alternative to replace diesel generators, but can also be used to e.g. power remote grids, balance power, enforce stability, and reinforce weak grids. The package is part of a concept which aims to ensure reliable energy storage and customize it to different demands. The system is based on a high safety standard, making it suitable for operation under harsh conditions and adaptable for transportation and redeployment.[87, 152]

**Table 9.4:** Specifications for Northvolt Voltpack Mobile System.[152]

| **Voltpack Mobile System** | |
|---|---|
| Installed capacity | 245 – 1225 kWh |
| DC-link voltage | 576 – 797 V |
| AC output voltage | 3 ph 400 V nominal |
| C-rate | Up to 1C |
| Power output | Up to 250 kW |
| Size | 2000 x 1600 x 1200 mm |
| Weight | <3000 kg |

The system delivers battery modules up to 250 kW and a capacity of 245 kWh, with the possibility of connecting five modules together in parallel to achieve a capacity of 1225 kWh. Based on trends in figure 5.8, a CAPEX of 8600 SEK/kWh was chosen for the batteries. In addition an expected lifetime of the batteries was set to 10 years, based on information in table 5.1. Other specifications of the Voltpack is shown i table 9.4.[87, 152]

To make the simulation as realistic as possible a charge and discharge rate based on SoC was added to the MATLAB simulation. This function is integrated in PSS. From the manufacturers, values for maximum charge and discharge power was given, and charge/discharge curves were made. The curves were based on figure 5.2, with optimizations to fit Voltpack batteries.

Degradation of the batteries based on the usage was added to create a more realistic value for the capacity of the batteries at all times. This was done using equation 5.2. This makes it possible to separate actual capacity and theoretical maximal capacity. The SoH for the batteries added at the different steps were separate, making it possible to see if they reach EoL before the theoretical lifetime.

Annual degradation rate is not added, so actual SoH for the batteries can be lower than what is given in the simulation. The batteries where removed from the simulation in MATLAB after 10 years, as this is theoretical lifetime. This was done to avoid giving an unrealistic lifetime for the batteries. If the batteries reach 70 % of SoH before ten years they were also removed. PSS does not remove batteries automatically after 10 years, but when SoH reaches 70 %.

### Emergency Power Supply

During a power outage an airport is responsible for multiple measures, such as making sure planes are able to land, and maintaining communication with air-traffic. The most crucial parts of an airport are on the airside, and it is vital to keep these functions running. There are laws and regulations in place to ensure emergency power is available and functioning. During a blackout normal operation ceases, including charging of planes. Power is only used for vital infrastructure.[30]

Today, two diesel generators are used as emergency power supply, with 315 kVA as standby start. The generators have previously been used in LPV operations, i.e. under poor visibility conditions. To prepare the airport for a low emission future, it is a necessity to remove the generators. In this thesis batteries are installed as emergency power supply and will be simulated separately. They are included in the economic evaluations, and are thought to be two Voltpack batteries.[66, 153]

### 9.2.2 Installation of a Solar Power System

A PV installation is used to produce local electricity in step 2 and step 3. The airport runway is in east-west direction, and the terminal is located north of the runway. After a meeting with the project leaders of Green Flyway and mailing with deputy director at Frösö Park, Fredrik Karlstedt, the chosen installation location for this thesis is at the roof of Building 90. The location of Building 90 at Frösö Park Arena is shown in appendix A.[27, 114]

Both ground-mounted and roof-mounted installations is of interest to Green Flyway. Jämtkraft has issued a possible PV ground installation, also illustrated in appendix A. This installation is closer to the airport and north of the runway. It consists of 1404 panels and is estimated to cost 3.8 MSEK.[154]

It is assumed that the PV type is the same as the one installed at Östersund Solar Park, GCL Monocrystalline. The solar conditions on the roof of Building 90 are analyzed using a Photovoltaic Geographic Information System, PVGIS, tool made by the European Commission. PVGIS chooses an optimal slope and azimuth, and has a default system loss of 14 %. In PVGIS, crystalline silicon is chosen as PV technology, 408.8 kWp is set as installed peak PV power and year span is chosen to be 2011-2016. Calculation on input values to the program is shown in appendix A, as well as calculations on the size of the installation. Table 9.5 shows specification for the GCL Monocrystalline Silicon installation at Building 90.[100]

**Table 9.5:** Specifications for GCL Monocrystalline Silicon at roof-mounted installation.

| **GCL Monocrystalline Silicon** | |
|---|---|
| Efficiency | 19 % |
| Number of panels | 1 320 |
| Total peak power | 408.8 kWp |
| Total roof area | 6 600 $m^2$ |
| Total weight | 24 tonne |
| Panel size | 1640 x 992 x 35 mm |
| Life expectancy | 30 yr |
| CAPEX | 3.8 MSEK |
| EPBT | 1 – 1.5 yr |
| Optimal slope v. vertical | 49° |
| Optimal azimuth | -6° |

Hourly radiation data with values on PV power output are extracted from the program. It is chosen to use PV power output given by the program instead of calculating power output using solar irradiance and panel efficiency. This is decided because the efficiency of a PV system is affected by several external factors, some of which are corrected in the power output from PVGIS. The corrected factors include shallow-angle reflection, effect of changes in the solar spectrum, system losses and degradation with age, and PV power dependence on irradiance and module temperature. Description of the corrected factors are found in appendix A.[155]

Factors not considered by PVGIS are snow, partial shadowing, and dust and dirt. Among these, snow is considered the factor with most impact on the simulated installation. If the modules are covered by snow, it can reduce the produced power up to 10 % in this period. A distance of 3 meters between each row is set to avoid overshadowing.

In order to create a representative PV power output, a method was used to base the production on several years. PV production for every hour in 2016 is found in PVGIS. This vector is adjusted by PV production from 2011 to 2016. A single mean value is calculated from mean values for every year. The PV production vector from 2016 is then multiplied with the ratio between the mean value. This method creates a new adjusted vector of PV production.

This vector is further adjusted with a reduction of 10 % due to the impact of snow in December, January, February and March. These are the months with greatest snow depth in Östersund. Figure 9.4 shows the daily power output from the PV installation including adjustments to consider snow over a year. Excess energy from PV production is sold to grid at spot price in simulation.

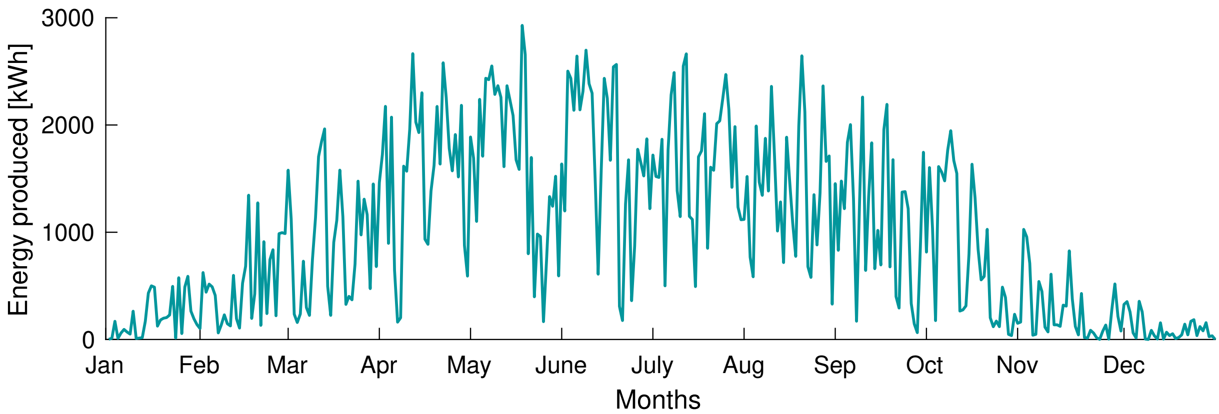


**Figure 9.4:** Daily PV energy output adjusted to snow at Building 90 throughout the year.[100]

### 9.2.3 Energy System

Design of energy systems are dependant on grid capacity, losses in various components and power consumption, as well as electricity costs if profitability is a decisive factor. Local grid capacity is crucial when electrifying an airport and when considering the energy storage quantity needed. Losses in cables and electrical components must be implemented to get a realistic result, as well as the power consumption at the airport aside from charging of planes.

#### Grid Subscription

Minimal information about grid upgrades is published, but it is assumed that measures will be made in the future. Table 9.6 shows grid subscription today and assumed grid subscription in the steps in the simulation. The assumptions are made after conversations with the local power company Jämtkraft. In addition a minimum value of 20 kW was decided to keep the space open for an increase in unforeseen load.[66]

**Table 9.6:** Grid subscription at different steps in simulation.[66]

| | |
|---|---|
| Current grid subscription | 390 kW |
| Step 1 | 1000 kW |
| Step 2 | 1000 kW |
| Step 3 | 5000 kW |

### Cables and Electrical Components

Losses in cables and electrical components are important to include in a representative simulation. Length of cables and distance from electrical substations at the airport is unknown. Values for efficiency of inverter, rectifier, fast chargers and cables are found in literature and implemented in the MATLAB simulation. PSS has built-in loss coefficients in the program. The efficiency of voltage converters in BESS was set to the same as the default value in PSS.[80, 156]

**Table 9.7:** Efficiency of electrical components.[80, 156]

| Component | Efficiency |
|---|---|
| Voltage converter | 95 % |
| Inverter | 94 % |
| Rectifier | 96 % |
| Fast chargers | 95 % |
| Cables | 80 % |

### Electricity Price

Spot prices for every hour in 2019 are based on hourly values from the Nordic power exchange, Nord Pool Spot. This vector is adjusted with values from 2014 to 2020, using the same method as for PV production.[157]

The spot price from Nord Pool Spot does not include costs from electricity certificate, energy taxes, value-added tax VAT, electricity network costs and other subcharges. Swedavia and Åre Östersund airport could not share this economical information because of confidentiality. The values in table 9.8 are estimates made by Jämtkraft and are added to the spot price to create a realistic electricity price. Electricity certificate, energy tax, subcharge from stock exchange and VAT are directly added to the spot price, while the fixed fee and subscription fee are yearly costs.[66, 157]

**Table 9.8:** Estimated grid costs added to the spot price.[66]

| | |
|---|---|
| Electricity certificate | 0.025 SEK/kWh |
| Energy tax | 0.26 SEK/kWh |
| Subcharge from stock exchange | 0.02 SEK/kWh |
| VAT | 25 % |
| Subscription fee | 337 SEK/kW |
| Fixed fee | 15 550 SEK/yr |

In simulations a distinction is made between high and low prices, based on the season. The system prioritizes using the batteries when prices are high, and grid when the prices are low. The batteries are also mostly charged when the price is low.

**Power Consumption**

Jämtkraft has shared the hourly power consumption at the airport from 2016 to 2019. There are large variations within a year which are important to include. The shape of each year's curve is similar, but fluctuations occur at different times every year. In addition to this, the average consumption had a sinking trend from year to year presumably due to energy efficiency at the airport. It is assumed that this trend will continue in the future.[66]

Different methods were considered to create a representative average graph for 2016 to 2019. None of these methods included the extent of the fluctuations and yearly deviations and was not representative as a typical curve. The different methods shaved peaks for both high and low consumption and removed natural variation which are necessary to recreate a representative yearly consumption. Because of this, the power consumption for 2019 without adjustments is chosen for the simulation.

### 9.2.4 Hydrogen

Hydrogen is not part of the simulation. Jämtkrafts evaluations have already ruled out local production at the airport within the simulation time frame. It is therefore only discussed as a component in the future in chapter 11.6. It is discussed both as fuel for planes, and as energy storage in the airport.

### 9.2.5 Microgrid Controller

For the simulation in PSS a microgrid controller, MGC, has to be chosen. It is a device that distributes energy resources and loads in an energy system by predictions. It connects every component and prioritizes actions based on monitoring. It continually measures and manages efficiency of every component in regards to status and health. The human interaction with the MGC happens through a Human Machine Interface.[158]

The MGC analyses energy cost and tariffs, in addition to $CO_2$ emission through energy monitoring of the PCC. In normal operation, the main function of the MGC is to peak shave the load using ESS and renewable energy production. It ensures maximum efficiency and cost-effective operation by optimizing. The integration of renewable energy is resource-efficient to meet climate protection targets. In addition it implements voltage control and load frequency control.[158]

When a microgrid is disconnected from the external grid, it is called islanding. In case of a blackout in the grid, the MGC detects it instantaneously, and takes action. It automatically starts the backup generators and prioritizes assets. The generators cooperate with other energy storage and renewable energy production on site. When normal power supply is restored, the MGC re-synchronizes with the grid.[158]

The specific MGC used in PSS uses a priority based system for dispatching, where the user needs to specify the priority of the assets and buses. It is mostly used for controlling small to medium scale hybrid power grids, that operate in conjunction with main grid connections. It is based on time-steps where it decides how to share loads based on current system state and power limit.[80]

## 9.3 Assumptions and Delimitations

As a result of limited resources and time restriction, assumptions and delimitations was a part of this thesis. Assumptions were formed in communication with specialists due to restrained access of data. These mainly include battery capacity, available grid capacity and number of PVs installed. Voltpack was the only battery considered. Testing of several battery types could be beneficial if realising the project. Inputs in simulation is based on battery packs. The quantity of batteries installed could possibly be reduced if considering modules.

The distribution network related to the airport is assumed to be stiff in order to withstand heavy loads when charging electric planes. The annual simulation is based on a charging sequence for planes where the same two weeks with variations are repeated. It aims for a sequence based on high season. However, larger seasonal and annual differences could occur, as well as unexpected technology development, making this an uncertain element. The test arena in step 1 is simulated with a set charging sequence although this pattern will be more flexible than the commercial departures in step 2 and 3. Power losses in components and cables in the energy system is based on theory and can differ from actual losses in the energy system.

Technology regarding several simulated components could be significantly improved as the simulation is based on future development. This especially applies to available chargers and PV efficiency. Simulation is based in today's technology. More powerful chargers are expected to be developed by the time larger planes are implemented in step 3 and trends indicate that PV efficiency will increase in the years to come.

Finally, this thesis is mainly a technical report, thus the economic aspects are minimised. All values in the economic assessment are presented in million Swedish Kroners, MSEK. Standard deviations are calculated but are not included in results if smaller than 10 000 SEK. Inflation is not included in calculations.

## 9.4 Economic Assessment

Economic considerations are important to validate the profitability of the project. Net present value and payback period is calculated in this thesis. The discount rate used is given in Avinors third quarter report from 2020 as 5.1 % for airport operations. Avinor utilize 4.5 % for Air safety, while Swedavia uses 8.2 % before taxes. Conversion factors used throughout the thesis is NOK to SEK 1.013, EUR to SEK 10.15 and USD to SEK 8.3.[159]

### Income from Planes Charging

The electrical aviation is very early in development, and regulations about costs of charging planes at airports are not yet set. It was therefore looked at other electric charger prices. The choice was to use the same prices as medium size fast chargers at charging stations in Norway for electric cars at the rate described in equation 9.1.

$$\text{Price for charging} = 75 \text{ SEK/h} + 3.2 \ \text{ SEK/kWh} \tag{9.1}$$

Using this price model for charging Heart Aerospace's ES-19 gives the value in table 9.9 for price per seat for a full tank. The other two planes in the table were filled with jet fuel, to compare costs per seat for a full tank. The table shows considerably lower costs for the electric plane, though it must be considered how jet fueled planes have longer range.[160, 161]

**Table 9.9:** Comparison full tank fuel prices.[160, 161]

| | **Heart Aerospace's ES-19** | **De Havilland Dash 8** | **Boeing 737-800** |
|---|---|---|---|
| Seats | 19 | 39 | 174 |
| Full tank fuel cost | 172 SEK/seat | 740 SEK/seat | 1345 SEK/seat |

### Net Present Value

Net present value, NPV, is used to evaluate the profitability of the simulation. The assessment returns all payments and withdrawals to the staring point of the simulation. The method is useful to determine if an investment will result in net profit or loss. A positive NPV indicates a profitable investment. Equation 9.2 shows NPV calculated with future savings $B$, $S$ as residual value from components, $N$ in years, $r$ as discount rate and $I$ is investment costs.[162]

$$NPV = -\frac{I_N}{(1+r)^N} + \frac{B_1}{(1+r)} + ... + \frac{B_N}{(1+r)^N} + \frac{S}{(1+r)^N} \tag{9.2}$$

$B$ is found for each component in the system per year of operations. While $I$ is the investment cost for all components at the year of investment. The discount rate is the most important parameter for the accuracy of the calculation.[162]

### Payback Period

Payback period states how long it takes to recoup an investment. It is the length of time it takes for an investment to reach a break-even point. It is calculated by withdrawing the undiscounted free cash flow from the investment price every year. The undiscounted free cash flow is OPEX subtracted from income. A cumulative free cash flow is then found by adding the value from the current year to the previous year. This value determines when the costs of the investments are returned by finding the break-even year. Equation 9.3 shows the payback period formula. Note that a cumulative method must be performed when using the formula.[163, 164]

$$PP = I_P + \frac{R}{I_{BE}} \tag{9.3}$$

In the equation $PP$ is payback period, $I_P$ is the cash inflow the preceding year, $R$ is the amount left to be recovered and $I_{BE}$ is the cash inflow in the break-even year.

## 9.5 Project Simulation

MATLAB and PSS DE®Siemens were used to make simulations of the energy system. PSS DE®Siemens has built-in microgrid controller while MATLAB does not. MATLAB is a software program used for programming equations and making calculations. Typical uses include algorithm development, modelling, simulation and prototyping, data analysis, exploration, visualization, and scientific and engineering graphics. PSS DE®Siemens is a simulation program made by Siemens used in energy consulting. It will further be referred to as PSS.

### Simulation in MATLAB

The flowchart describing the MATLAB code is found in attachment B. The code prioritise using PV when available, and checks the electricity price compared to a maximum price described in chapter 9.2.3. When the electricity price is high the battery is prioritized as power supply, as long as the SoC is over 35 %. If the electricity price is low and there is more power available after satisfying loads the battery is also charged. If the grid and battery can not satisfy all loads the charging demand is carried on to the next hour, meaning a slower charge for the planes.

When there are no planes the code checks SoC of batteries and electricity price, when both are low the batteries are charged. Because of security of supply the batteries are charged when below 60 % SoC regardless of price. Resting SoC was set to 90 %. The simulation lasts for 15 years, with step 1 being the start of the simulation.

### Simulation in PSS DE®Siemens

In PSS the project was simulated in a 20 year perspective, from 2020 to 2040. The same input data was used as in MATLAB. PSS uses a microgrid controller, which optimizes the system. To influence the controller, different incentives and thresholds were adjusted to achieve the desired operations. In addition, different variations were created to simulate the system with and without PV installations. The programs default values for loss and efficiency of the different components were used.

# 10 Results

Results from MATLAB and PSS will be presented together in this chapter, with results for the whole time period and for each step. The simulation in MATLAB simulates a time period of 15 years beginning in step 1, followed by step 2 after five years and step 3 after ten years. PSS simulates a project lifetime of 20 years where step 1 begins after five years. PSS simulations need to start five years earlier to match MATLAB because of economic assessments implemented in the program. The largest difference between the two software is the microgrid controller in PSS, compared to manual prioritizing in MATLAB. This will affect the results.

## 10.1 Current Situation

The current situation at the airport includes the grid connection and airport power consumption, and is used as a reference in the simulation. Before simulating future consumption and need, an analysis of the energy system today was done giving the following results in table 10.1. The airport is connected to a district heating system, so electricity does not cover this. As seen in the table, values for mean and minimum available power are very low, making an increasing power demand hard to withstand.

**Table 10.1:** Statistics for power and electricity cost at the airport today.

| | | **Today** |
|---|---|---|
| Cost of electricity | [MSEK/yr] | 1.2 |
| Mean available power | [kW] | 232 |
| Min. availabe power | [kW] | 18 |
| Grid subscription | [kW] | 390 |

Two batteries are installed as emergency power supply. A simulated blackout where the grid is set to zero shows various results in MATLAB and PSS. The test is performed in the winter, as this is the season with highest consumption. Both 100 % and 40 % of airport load was tested. The results are shown in table 10.2. MATLAB can cover 100 % load for 12 hours longer than PSS and 40 % for 6 hours longer. Public information about operating time of emergency power supply is not possible to obtain. Therefore an operating time of 24 hours for 40 % of load was assumed to be sufficient. Both MATLAB and PSS can cover this with two emergency power batteries. This can be the result of the programs using different discharge patterns based on SoC.

**Table 10.2:** Emergency power supply battery performance in simulated blackout.

| | | **MATLAB** | **PSS** |
|---|---|---|---|
| 100 % airport load | [h] | 24 | 12 |
| 40 % airport load | [h] | 30 | 24 |

## 10.2 Project Results

Project results include important simulation data, specific results for each step and trends for the whole simulation timeline from both MATLAB and PSS. Grid subscription, maximum load and number of batteries installed in step 1, 2 and 3 is presented, as well as highest load increase and cost of operations. CAPEX and OPEX for each step is shown in appendix C. SoH for the total installed BESS at the end of step 2 and 3 are also studied. Lastly, BESS and PV utilization results are presented.

Total load each month of the year for all three steps, explained in chapter 9.1, as well as current load is shown in figure 10.1. Compared to airport load today, the load in step 1 increases by 54 % considering the whole year. The load in step 2 increases with 158 %, while the load in step 3 increases significantly with 570 %. As a delimitation the same increase in plane charging demand is used for the entire year. Seasonal variations are best illustrated by looking at current airport load which is 45.6 % higher in January compared to July. As the load increases, seasonal variations have a smaller impact on the total power demand.

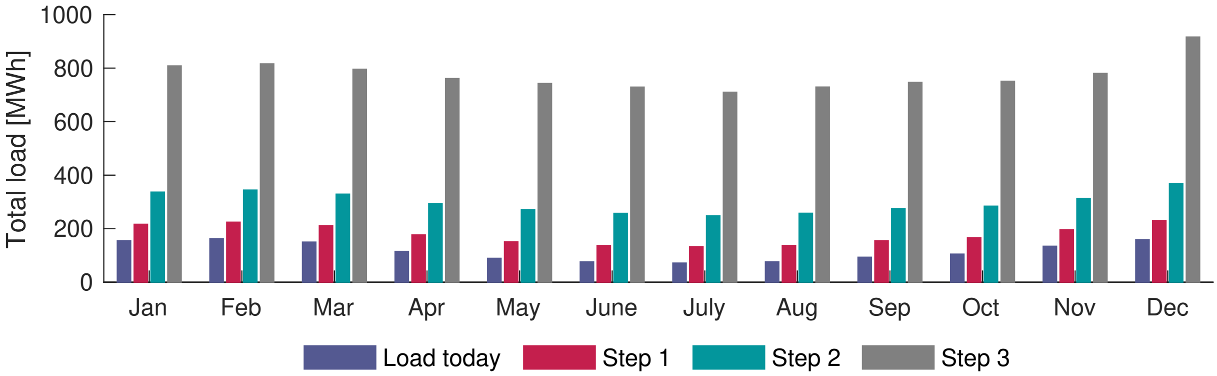


**Figure 10.1:** Total load at the airport throughout the year, today and for all three steps.

PSS provides an overview of the different steps, as well as a total overview. Table 10.3 shows the energy distribution in each step from PSS. The annual energy production and exported energy are related to the energy produced by and sold from PV. This is why there is no production in step 1. Less PV electricity can be exported in step 3 compared to step 2 because the load is significantly larger at the airport. Implementation of PV is a source of self sufficiency and covers 4.8 % of the total energy consumption in the project. The imported energy in the table is from the grid, while electrical consumption is the total consumption at the airport in each step.

**Table 10.3:** Annual energy distribution from PSS with PV in all three steps.

| | | Step 1 | Step 2 | Step 3 |
|---|---|---|---|---|
| Energy production | [MWh/yr] | 0 | 367 | 355 |
| Exported energy | [MWh/yr] | 0 | 20 | 13 |
| Imported energy | [MWh/yr] | 2155 | 3317 | 8976 |
| Electrical consumption | [MWh/yr] | 2133 | 3577 | 9284 |

An overview of the total distribution for the entire timeline of 20 years from the simulation in PSS is shown in a sankey diagram in figure 10.2. It illustrates how PSS evaluates the profitability of battery use compared to grid costs over the total project lifetime. Battery use is very dependent on the grid subscription and total load at the airport. Sankey diagrams for step 1, 2 and 3 is shown in appendix D. BESS are used most in step 2, where 10 % of the total energy from grid and PV is stored in the batteries. In the total overview, 2.8 % of the energy is stored in the batteries, indicating a smaller share in step 1 and 3. The total overview shows that 4.4 % of PV production is sold to the grid.

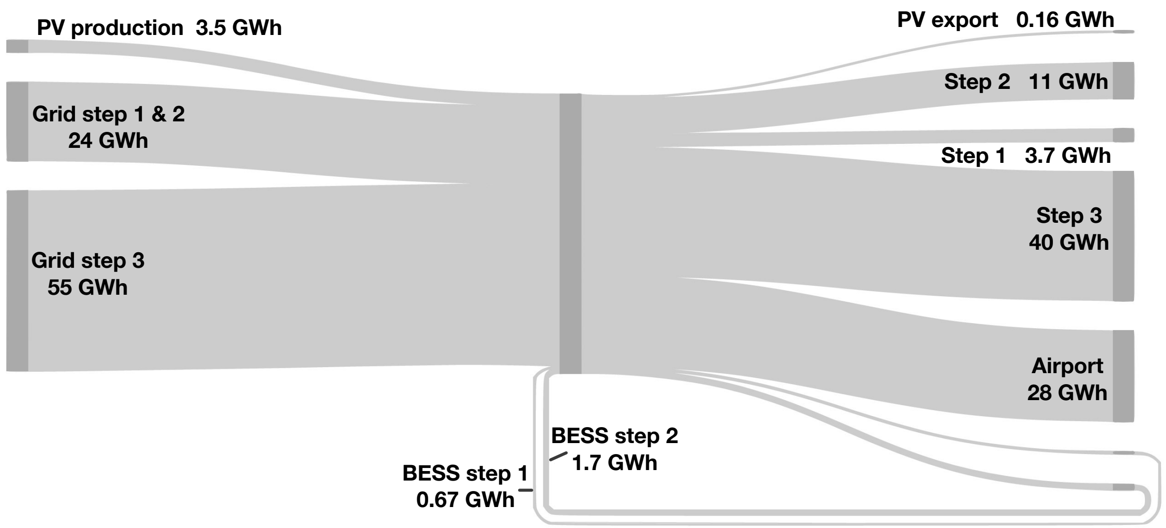


**Figure 10.2:** Sankey diagram showing total project energy flow from PSS. Edited from original.[80]

A combination of power for charging planes, grid capacity, PV production and energy in the batteries for 24 hours in April is shown in figure 10.3. The data is from step 2, but represents a daily pattern for these components in all three steps.

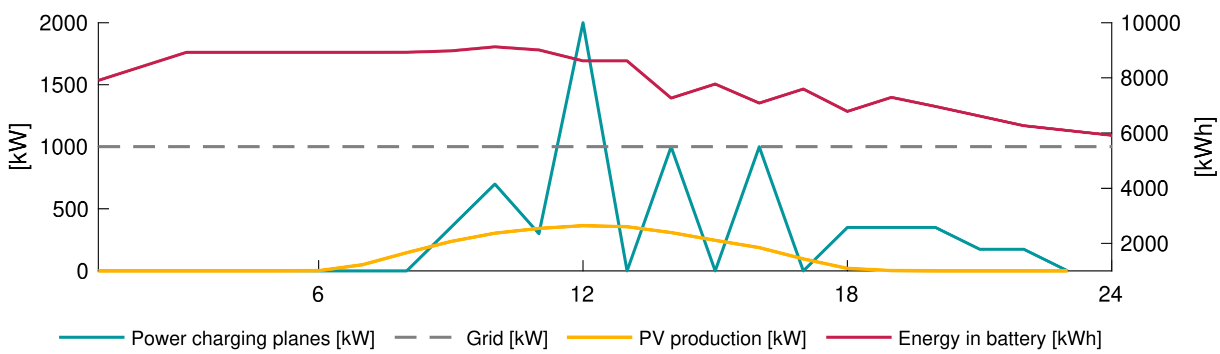


**Figure 10.3:** Power and energy utilization for 24 hours in April in step 2.

The figure visualizes how use of the batteries is connected with load. Power charging planes, grid capacity and PV production is stated in kW in the left y-axis, and energy in the battery in kWh in the right y-axis. Power charging planes is a total load for all planes charging throughout the day. During the day, the power for charging planes is high, indicating fast charging. The low slope in the evening indicates slower charging. Energy in battery shows how the battery is used to charge the planes, and when the planes are done charging the battery is charged again. This is illustrated well between hours 12 and 18, when the energy in the batteries increase in the periods when there is no charging demand.

### 10.2.1 Step 1 Test Arena

Step 1 is a test arena and describes the vision of becoming the optimal location for training pilots and testing small and large electric planes. In step 1 the grid subscription is increased to 1000 kW, and the test arena plane charging sequence is implemented. Maximum load consisting of consumption at the airport and the new plane charging sequence is 1352 kW, 35 % higher than the grid subscription. Batteries needed and grid subscription is shown in table 10.4. Two batteries added give a total energy of 2450 kWh.

**Table 10.4:** Number of batteries installed and grid subscription in step 1.

| | | **MATLAB** | **PSS** |
|---|---|---|---|
| Installed BESS without PV | | 2 | 2 |
| Grid subscription | [kW] | 1000 | 1000 |

The grid can at many times tolerate the load from charging alone. In the winter months extra power is needed to meet demand. In MATLAB, two batteries can withstand a load increase of 9.0 % without blackouts. In PSS the system with batteries can withstand a 16 % increase of load without blackout.

Table 10.5 shows yearly costs from MATLAB and PSS for step 1 both with and without batteries added. CAPEX is a one time expense in the first year in the step. OPEX include grid subscription and operational expenses for batteries. If batteries are not added the grid needs to be increased to 1380 kW. This is higher than grid subscription at the moment. Cost of electricity is lower with BESS because the batteries can charge when the electricity price is low and can be used when the price is high. Cost of electricity is 2.2 % higher for PSS than MATLAB, this can be caused by differences in priorities in the programs. A full overview of costs can be found in appendix C.

**Table 10.5:** Costs of operations and investments in step 1.

| | | **BESS** | **No BESS** |
|---|---|---|---|
| Cost of electricity MATLAB | [MSEK/yr] | 1.84 | 1.92 |
| Cost of electricity PSS | [MSEK/yr] | 1.88 | 1.92 |
| Increase of subscription fee | [MSEK/yr] | 0.205 | 0.330 |
| CAPEX | [MSEK] | 42.3 | 0 |
| OPEX | [MSEK/yr] | 0.393 | 0.353 |

### 10.2.2 Step 2 Airborne Shuttle Traffic

Airborne shuttle traffic refers to ES-19 operating in shuttle traffic. In this part of the simulation, PVs are installed. For the following years results will show values both with and without PV. The load increases as the planes are bigger with more energy storage. The grid is still set to 1000 kW and the highest load is 2291 kW, 130 % higher than grid subscription. The period with the highest loads is in the winter when the production from PV is low. Table 10.6 shows how many batteries are installed in step 2, with and without PV, as well as grid subscription from both MATLAB and PSS.

**Table 10.6:** Number of batteries installed and grid subscription in step 2.

| | | MATLAB | PSS |
|---|---|---|---|
| Installed BESS with PV | | 4 | 3 |
| Installed BESS without PV | | 4 | 4 |
| Grid subscription | [kW] | 1000 | 1000 |

In MATLAB, four batteries are added to withstand this load, combined with batteries from step 1 resulting in a total of six batteries. This gives a maximum energy of 7350 kWh and a discharge power of 1350 kW. Both with and without PV the system can withstand an increase of load of 3.0 %. Making step 2 less flexible compared to step 1.

In PSS the increased load from the new charging sequence makes it necessary to install 3 new batteries when including power from PV, and 4 new batteries if the PV is not installed. The system with PV can not withstand an increase in load and the the system without PV can withstand 12 % load increase. The system without installed PV have 20 % higher BESS capacity, to compensate for the power from PV.

Table 10.7 shows SoH for the batteries after fives years of operation. At the end of step 2, the batteries from step 1 in MATLAB have reached expected lifetime since they have been in use for 10 years. They still have a very high SoH, indicating that the batteries have not been used to their full potential. Batteries installed in step 2 have been in operation for five years, but have a higher SoH than the age of the battery should indicate. The total SoH without PV is 0.6 percentage point lower than with PV.

**Table 10.7:** SoH for batteries installed in step 1 and step 2, at the end of step 2.

| | Batteries step 1 | Batteries step 2 | Total |
|---|---|---|---|
| With PV MATLAB | 91.8 % | 93.2 % | 92.7 % |
| Without PV MATLAB | 91.4 % | 92.5 % | 92.1 % |
| With PV PSS | 97.8 % | 98.9 % | 98.5 % |
| Without PV PSS | 97.6 % | 98.7 % | 98.3 % |

In PSS the batteries from step 1 and 2 have a very high SoH. Because of this the batteries from step 1 are still in use further in the simulations. Total SoH for the batteries is 0.21 % higher for the BESS combined with PV than without. If no batteries are added and only the two batteries from step 1 are used, all loads can not be covered in either simulations. This would lead to slower charging for the planes. Furthermore SoH for the batteries would decrease rapidly, and reach EoL before ten years.

Table 10.8 shows yearly costs from MATLAB and PSS in step 2. It is not possible for the system to function with the grid subscription set, without installing BESS. It is still added to showcase the differences in cost in case the grid capacity turns out to be larger than assumed. Both cost of electricity and subscription fee is higher without BESS, showcasing how the batteries help shave peaks and even out the loads. The investments in batteries is not needed without BESS, making CAPEX significantly lower. The difference between installing PV or not is also visible in the costs. The cost of electricity is reduced by 6.9 % in MATLAB and 9.4 % in PSS. A full overview of costs can be found in appendix C.

**Table 10.8:** Costs of operations and investments in step 2.

| | | BESS | BESS and PV | No BESS |
|---|---|---|---|---|
| Cost of electricity MATLAB | [MSEK/yr] | 2.95 | 2.76 | 3.10 |
| Cost of electricity PSS | [MSEK/yr] | 3.23 | 2.96 | 3.10 |
| Total subscription fee | [MSEK/yr] | 0.337 | 0.337 | 0.779 |
| CAPEX | [MSEK] | 42.3 | 46.1 | 0 |
| OPEX | [MSEK/yr] | 0.393 | 0.423 | 0.353 |

### 10.2.3 Step 3 Larger Electric Planes

Step 3 is a continuation of the ES-19 airborne shuttle traffic but with introduction of larger electric planes. With the implementation of these planes, the grid is increased to 5000 kW and no new batteries are needed in both MATLAB and PSS. The maximal load is more than doubled compare to step 2, with 5313 kW. Load is 6.3 % higher than grid. PV production is considerably lower than loads in step 3, results are therefore approximately equal with and without PV.

In both simulations batteries from step 2 are enough to satisfy all loads. In MATLAB four batteries from step 2 are used, but only two batteries are needed to cover load. The two extra batteries can therefore act as emergency power supply as SoH is very high. The system can withstand a load increase of 3.0 % both with and without PV.

In PSS the batteries installed in step 1 have not reached EoL and are still in use. Lifetime was set to 10 years in the program. The program overrides this and still uses the batteries after end of lifetime is reached. Because of this it is not necessary to install new batteries in PSS in addition to the 5 and 6 previously installed. The system with PV and 5 batteries can withstand a 19 % load increase, and without PV 6 batteries can withstand 24 %. Table 10.9 shows SoH for the batteries after five years of operations in step 3.

**Table 10.9:** SoH for batteries installed in step 1 and step 2, at the end of step 3.

| | Batteries step 1 | Batteries step 2 | Total |
|---|---|---|---|
| MATLAB w PV | - | 80.0 % | 80.0 % |
| MATLAB w/o PV | - | 79.8 % | 79.8 % |
| PSS w PV | 96.8 % | 97.8 % | 97.4 % |
| PSS w/o PV | 96.3 % | 97.4 % | 97.0 % |

Both with and without PV in MATLAB, the batteries have a high SoH at EoL, about one third left. At this stage the maximal load is only 6.3 % higher than the grid, and the grid can at many times withstand all load. The biggest reason to have batteries in this step is to be able to withstand fast charging and a high number of planes charging at once. In PSS the SoH for the BESS from step 1 and 2 is still very high, with over 27 percentage points left before EoL.

Yearly costs from MATLAB and PSS in step 3 are shown in table 10.10. Trends are similar to step 2, with higher electricity cost and subscription fee for no BESS, and lower electricity cost with PV. CAPEX is not included as there are no investments in step 3. A full overview of costs can be found in appendix C.

**Table 10.10:** Costs of operations and investments in step 3.

| | | BESS | BESS and PV | No BESS |
|---|---|---|---|---|
| Cost of electricity MATLAB | [MSEK/yr] | 7.24 | 6.92 | 8.30 |
| Cost of electricity PSS | [MSEK/yr] | 7.83 | 7.65 | 8.30 |
| Total subscription fee | [MSEK/yr] | 1.70 | 1.70 | 1.80 |
| OPEX | [MSEK/yr] | 1.74 | 1.77 | 1.70 |

Increasing the grid from 1000 kW to 5000 kW is an abrupt transition. Figure 10.4 shows a correlation between grid subscription and total number of batteries needed to satisfy all loads in MATLAB and PSS in step 3. The figure shows a decrease in the total number of batteries as the grid subscription increases. If batteries are not necessary in the future, it is possible to phase out the batteries as the grid subscription gets higher using a model similar to figure 10.4.

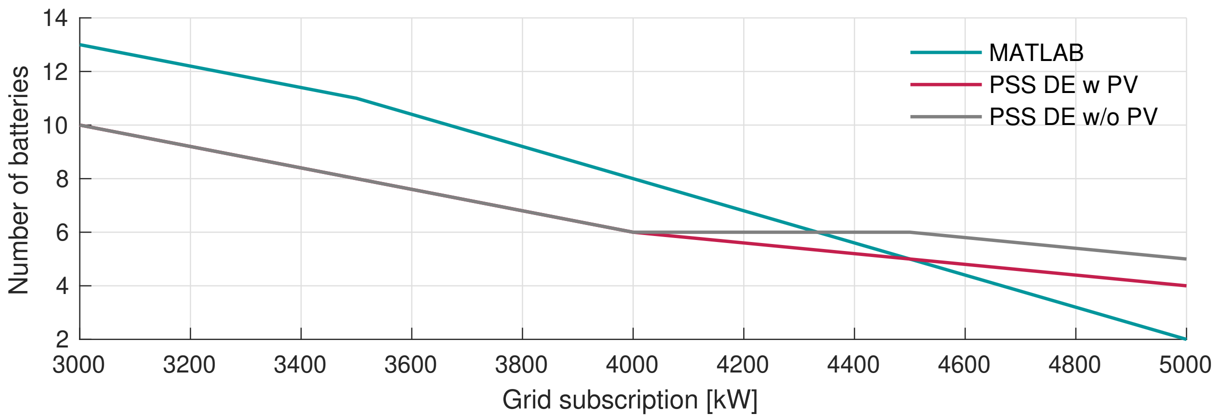


**Figure 10.4:** Total number of batteries and grid subscription needed to avoid blackouts.

### 10.2.4 Batteries over Project Lifetime

Battery life is highly dependent on the usage of the battery. To see how the different steps affect the lifetime, mean SoC and SoH was evaluated for the BESS, as well as impact of numbers of cycles on SoH.

Mean SoC with and without PV for the whole simulation from MATLAB and PSS is illustrated in figure 10.5. PSS use a smaller window of available SoC, evenly between 50 and 60 %. In MATLAB SoC is affected by how much time the batteries have to charge between usage. High usage correlates with a lower mean SoC, as the battery does not have time to fully charge. The MATLAB code is set to have a resting SoC of 90 %, significantly higher than PSS with a default resting SoC at 50 %. It is not possible to alter the default resting SoC in PSS. The microgrid controller used in PSS most likely evaluates that having a higher resting SoC is not needed to cover all loads in the system.

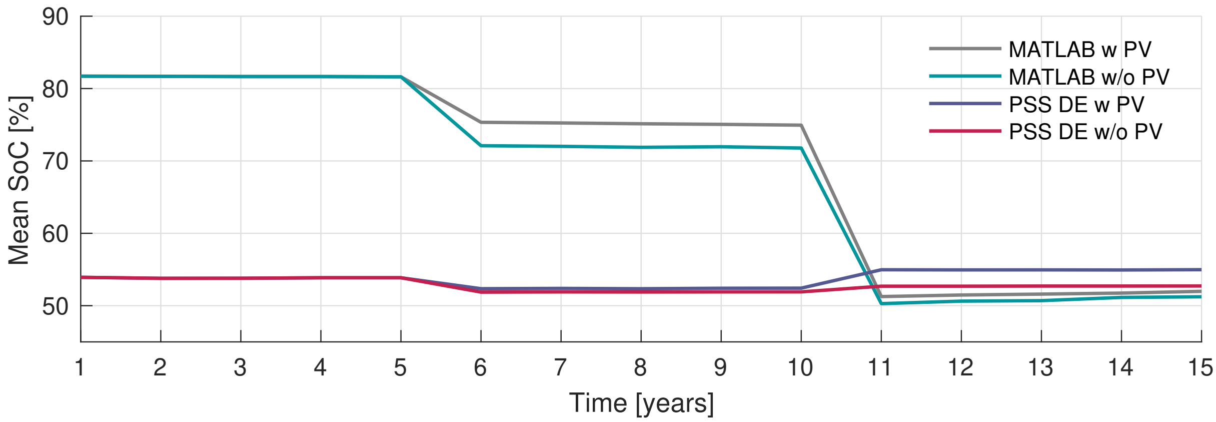


**Figure 10.5:** Mean SoC every year in the simulation with and without PV from MATLAB and PSS.

For MATLAB mean SoC with PV is slightly higher because the batteries are used less and have more time to charge. For PSS, using PV means that one less battery is needed leading to higher battery usage and a lower mean SoC. The mean SoC decreases after five years when step 2 is implemented. The power demand is higher, this requires more use of the batteries. This trend is illustrated by both MATLAB and PSS.

After 10 years the mean SoC decreases further in MATLAB and has a small increase in PSS. Having a mean SoC of around 50 % means SoC mostly varies between 20 and 80 %. For MATLAB mean SoC decreases about 30 % from step 2. The decrease of SoH over time affects charging and discharging rate of the batteries. Actual capacity $E$ decreases compared to theoretical maximum capacity $E_0$, as seen in equation 5.3. This means that each time equation 5.1 is used, charging and discharging has a bigger impact on SoC. In PSS SoH has only decreased 3 percentage points from the start of the simulation, so this has minor effects in this simulation.

5000 cycles were used in the simulation in MATLAB. Simulation in MATLAB was done with cycles between 2000 and 10 000 to see the effects cycles have on SoH. Results of this is shown in figure 10.6. Number of cycles needs to be at least 4000 to stay above 70 % SoH until EoL. The SoH increases after five years because more batteries are added, and again after ten years when the batteries with lower SoH installed in step 1 are removed. At 70 % the batteries are cut off in the simulation, explaining the flat slope in the figure when SoH reaches 70 %. A similar simulation in PSS has small variations for realistic number of cycles. This results in a lower limit of only 800 cycles to stay above 70 % SoH until EoL.

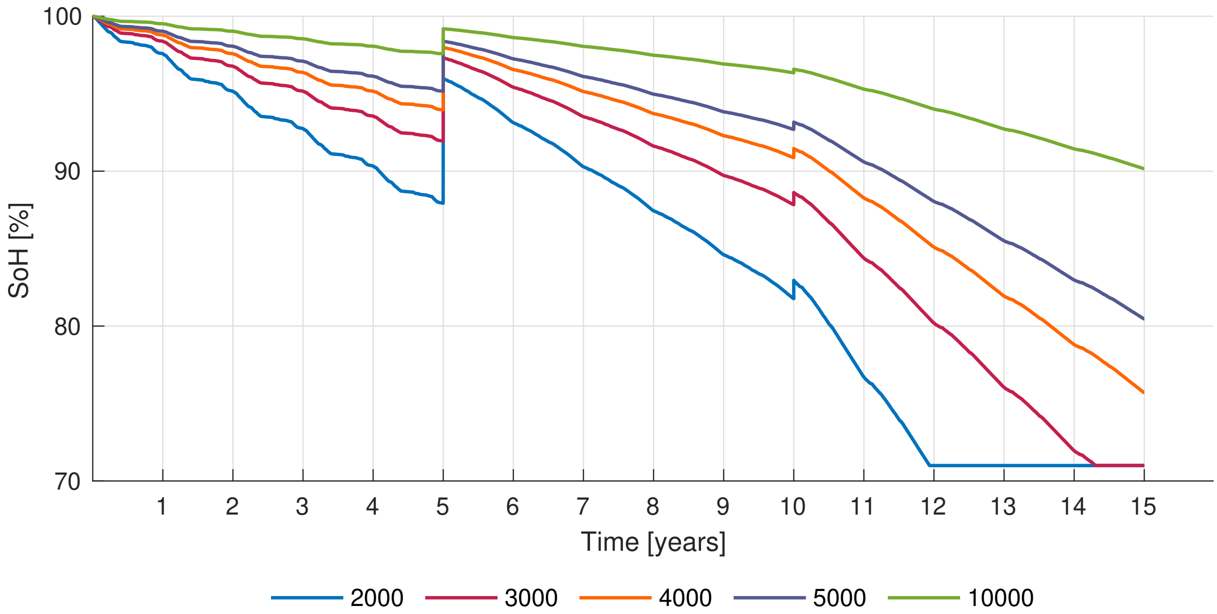


**Figure 10.6:** Decrease in SoH for BESS in MATLAB for given number of cycles.

### 10.2.5 Solar Power System Utilization

Electricity produced from PV is utilized to charge planes and batteries, consumption at the airport and export to grid. Figure 10.7 shows utilization of electricity from PV for two days with different PV production from June in step 3.

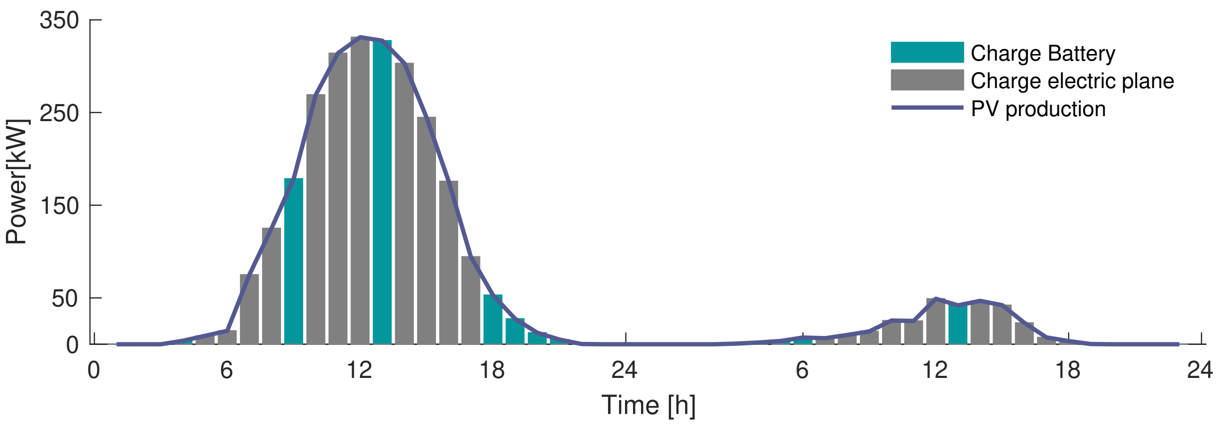


**Figure 10.7:** Distribution of electricity from PV production for two days in June in step 3.

In step 2, 40 % goes to charging batteries, 59 % to charging planes and the last 1 % to a combination of consumption at the airport and export to grid. In step 3, 18 % goes to charging batteries, 80 % to charging planes and the last 2 % for consumption and export. It is important to note that solar production is always lower than the hourly charging demand. PV is not alone responsible for all charging in the gray and blue parts of the figure, but in combination with batteries or the grid.

PV contributes to reducing load demand needed to be covered with electricity from the grid. The planes mostly need charging during the day, when solar production is at its highest. As seen in table 10.8 and 10.10, PV decreases the electricity bill and supplies the system with renewable power. In step 2 in MATLAB the electricity cost is 6.9 % lower with PV, and in step 3 the cost is 4.2 % lower. In PSS, it is 9.4 % lower in step 2 and 2.7 % lower in step 3.

PSS includes degradation of the PV system. From the installation of PV to the end of the simulated lifetime, the PV system has degraded with 6.1 %. Examining the PV produced gives an annual degradation of approximately 0.7 % for the PV installation. The degradation can be visualized by the produced and exported energy in table 10.3 where the produced energy from PV is reduced by 3.5 % from step 2 to step 3.

### 10.3 Economic Assessments

The economic results are calculated over a timeline of 20 years where step 1 is implemented after 5 years, step 2 after 10 years and step 3 after 15 years. Calculations are executed with equations presented in chapter 9.4 and are based on technical and simulated results. The parameters examined to understand the profitability of the project are NPV and payback period. The discount rate used in economic calculations is 5.1 %. An economic analysis is important to provide information about the profitability of the investment to investors.

Table 10.11 shows the economic results calculated based on MATLAB simulation. It shows the difference between the system with BESS and the system with both BESS and PV.

**Table 10.11:** Net present value and payback period results from MATLAB.

| | | BESS and PV | BESS |
|---|---|---|---|
| Net present value | [MSEK] | 0.293 | 0.230 |
| Payback period | [yr] | 16.3 | 16.2 |

Table 10.12 shows economic results calculated by PSS. These values are not representative for the simulation, as it was not possible to set a discount rate in PSS. The background of the results is unknown and the values will therefore not be discussed or compared to MATLAB.

**Table 10.12:** Net present value and payback period results from PSS.

| | | BESS and PV | BESS |
|---|---|---|---|
| Net present value | [MSEK] | 26.7 | 57.7 |
| Payback period | [yr] | 18 | 13 |

For NPV a residual value must be added. In MATLAB this was set to 33.3 % of purchase cost for PV. Batteries have reached EoL at the end of the simulation, and therefore have no residual value. In PSS batteries from step 1 have 61.7 % residual value, while batteries from step 2 have 63.0 % and 63.1 % respectively with and without PV. There was no residual value for PV in PSS.

## 10.4 Life Cycle Assessment

LCA analysis is performed on batteries and PV system installed in the project with numbers based on research. Carbon footprint from theory is used to calculate the weight quantity of $CO_2$-equivalents from production- and use-phase for both components. Emissions from the production phase is based on theory, so actual values for production can be lower. Values below must therefore be seen as indicative and not accurate. The emissions in the use-phase are calculated based on a timeline of five years in each step.

For batteries, LCA is divided into production and use phase for five years in each step, results can be seen til table 10.13. In step 3 there is no new batteries, hence no production emissions. The production phase accounts for the largest emissions, and are based on the capacity of the batteries. From theory 73 kg $CO_2$-eq/kWh was used. The use phase is based on the electricity supplied to the batteries from the grid, and is therefore dependent on the Swedish energy consumption mix of 52 g $CO_2$-eq/kWh.

**Table 10.13:** LCA analysis of production and use of batteries.

| | | **Step 1** | **Step 2** | **Step 3** |
|---|---|---|---|---|
| Production of batteries | [tonne $CO_2$-eq] | 358 | 358 | – |
| Use of batteries | [tonne $CO_2$-eq] | 61.6 | 392 | 253 |
| Total | [tonne $CO_2$-eq] | | | 1423 |

Calculations performed to find emissions from the PV installation includes production, transportation and installation. Based on theory, emissions from use-phase is neglected. It is assumed that components in the installation are not damaged and does not need to be replaced. By using 25.6 g $CO_2$-eq/kWh from PV carbon footprint theory, a total of 9.42 tonne $CO_2$-eq is calculated for the PV installation.

## 10.5 Sensitivity Analysis

Sensitivity analysis aims to analyse which parameters have the biggest impact on the results, durability of the system and the profitability. Some sensitivity properties have already been evaluated in the earlier respective chapters, such as maximum load increase and grid capacity without BESS.

### Solar Power System

In PSS, step 2 works with one less battery when PV is installed. In order to know if the system will function without blackouts if PV energy production is significantly reduced, the production is halved. This test was important because there is a possibility that production from a PV installation on Building 90 has to be shared with Frösö Park. Results display that the program runs without blackouts with halved PV production. For MATLAB the same number of batteries are used regardless of PV installation, a similar simulation would therefore not be necessary.

Simulation was also performed in MATLAB and PSS with double PV production as both ground- and roof-mounted installations are possible. This did not affect the number of batteries needed in each step. The winter months have the highest loads but the lowest production from PV, therefore this increase has minimal effect. The annual cost of electricity follow the same trends as in earlier results and is thus reduced.

A simulation with PV installed earlier was tested to know how a PV installation could affect results in step 1. It was not possible to have only one battery in step 1, even with PV. An earlier installation would therefore have minimal effect on economic results for the total project, as battery investments are a significantly larger expense.

**Batteries**

Batteries are the most crucial component in the simulation. The number of batteries determines whether there will be blackouts or not. The amount of load increase tolerated in the simulations is commented on in the respective chapters earlier.

Batteries used in the simulation reach EoL at 70 % SoH. Normal theoretical SoH at EoL is between 70 and 80 %. A simulation showing number of cycles and SoH was done with EoL at 80 %, to see how this affects number of cycles chosen. Figure 10.8 shows the results of this. The MATLAB simulation uses 5000 cycles, and would reach 80 % after exactly 15 years. This simulation was not performed in PSS because of low variations in SoH.

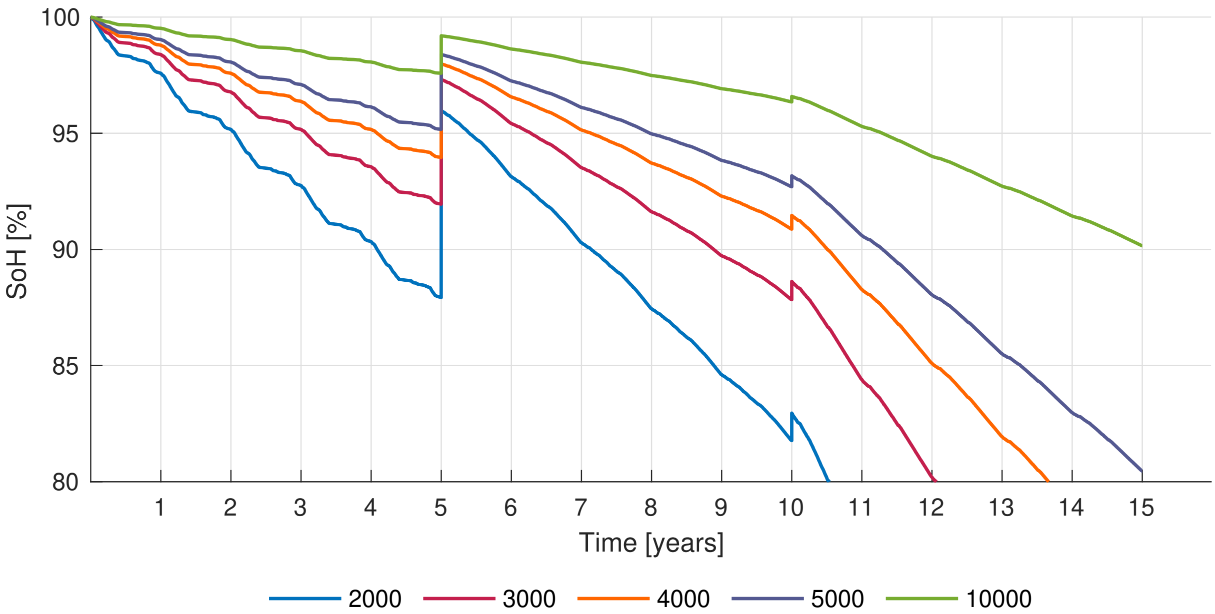


**Figure 10.8:** Sensitivity analysis of EoL with 80 % SoH.

### Economic Parameters

Each year in the simulation have greater income than costs. The biggest contributor to project costs is the CAPEX for batteries, at about 10 MSEK per battery. CAPEX for PV have minimal impact compared to the batteries. OPEX values for PV and batteries are quite low, making minimal differences in total economic results. A big contributor is income from planes charging. The income rate for charging used is not based on knowledge of price developments in aviation industry, but from charging of electric cars. A sensitivity analysis is preformed on economic parameters by adjusting income from charging of planes.

A simulation was performed with a charging price equal to spot price + 20 % to see how it affects the economic values. A simulation was also done with removing the airport fee, as well as removing fixed hourly charging price of 75 SEK/h in equation 9.1. Lastly the price is reduced from 3.20 SEK/kWh to 1.50 SEK/kWh to see how it affects the results. Tables 10.14 and 10.15 shows the effects the different income prices have on the economic profitability of the project.

**Table 10.14:** Altered charging income effect on net present value in MATLAB.

| Net present value | | BESS and PV | BESS |
|---|---|---|---|
| Spot price + 20 % | [MSEK] | - 51 | - 52 |
| Removed airport fee | [MSEK] | - 9.7 | - 10.3 |
| Removed 75 SEK per hour | [MSEK] | 0.79 | 0.15 |
| Reduced price from 3.20 to 1.50 | [MSEK] | - 39 | - 40 |

**Table 10.15:** Altered charging income effect on payback period in MATLAB.

| Payback period | | BESS and PV | BESS |
|---|---|---|---|
| Spot price + 20 % | [yr] | 23.7 | 23.3 |
| Removed airport fee | [yr] | 17.0 | 16.8 |
| Removed 75 SEK per hour | [yr] | 16.9 | 16.7 |
| Reduced price from 3.20 to 1.50 | [yr] | 21.5 | 21.1 |

Using spot price + 20 % has the biggest impact on profitability and payback period. This was expected, as this gives the lowest income. This sensitivity analysis demonstrates how important this income is, and why this needs to be evaluated thoroughly when electric planes become commercialized.

# 11 Discussion

This chapter further comments and discuss the results and components in the thesis. The discussion also addresses the future of the emission free aviation industry, and further work that can be completed as more research in the field is executed. Development towards a sustainable and electric aviation industry has already started and indicates a promising future. The Paris Agreement commits all countries to reduce GHG emissions. In addition, *the Nordic Declaration on Carbon Neutrality* has a large focus on reducing GHG emissions from the transport sector. Electric cars, buses and ferries, as well as various renewable fuels, have already advanced as renewable solutions.

The aviation industry is expected to be responsible for 15 to 27 % of global GHG emissions by 2050, which is an increase of up to 25 percentage points from today. This could have drastic consequences for the environment and measures must be implemented rapidly. Norway has a goal of 100 % electric domestic aviation by 2040, while Sweden has a goal of fossil free domestic aviation by 2030. These objectives are important for public and political investment in an electrified and sustainable aviation industry.

As the Green Flyway project will be finalized in the autumn of 2022, it is likely that new projects will develop in the future and continue where Green Flyway left off. Åre Östersund airport wants to be a test arena for emission free aircrafts in the near future. It is therefore very essential that the airport is able to withstand the charging demand from the planes and other infrastructure it brings with it.

In addition to having a unique Nordic climate, to attract electric aviation developers it is important with a sustainable energy and charging system. It is crucial to be able to support the future growth in the aviation industry. The main goal is to maintain a constant charging power and speed for the planes to satisfy both developers and costumers needs.

This discussion evaluates technical results and considerations in conjunction with theoretical points. Further an economic assessment is also completed, evaluating the profitability of the project. Results from each step and the total simulation is discussed, as well as different components impact on the energy system. Safety aspects specified to airports and of installed components are also considered. Life cycle assessment of batteries and PV is evaluated, in addition to further work of the project and predictions on the future of emission free aviation.

### Importance of Energy System Development

Energy systems are extremely dependent on the grid subscription and capacity. With the increasing electrification a choice must be made if grid subscription should be increased or if a more comprehensive local energy storage system should be implemented. This is mainly decided based on local grid capacity. Many of the Swedish power lines have reached the end of their lifespan of 40 years. Old grids are weaker, and do not have the capacity for load increases. Until Swedish grids are upgraded more local energy storage systems are needed as more energy and power intensive industries are established.

Current grid capacity in Östersund can not handle the large load increase electric planes will cause as the electrical aviation field is developed. With todays capacity the grid can tolerate step 1 and step 2 with energy storage, but can not handle the large load increase of step 3 without increases in grid subscription. As seen in figure 10.4 the number of batteries needed as energy storage is very dependent on the grid subscription in step 3. The total number of batteries at increasing grid capacities decreases close to linearly.

## 11.1 Simulation

Simulations of the energy system was done in MATLAB and PSS. To have two different simulations giving similar results was seen as a great advantage to validate the results. Some built-in values and commands in PSS can not be accessed by the user of the program and it is therefore difficult to know how these affect results. The main purpose of the simulation was to understand the energy demand needed for Åre Östersund airport to work as a test arena and further operations as a sustainable airport.

The charging sequence of planes used in the simulation are an estimation, based on conversations with the leaders of Green Flyway. At this stage it is not possible to know if the chosen patterns are reasonable. When developing the charging sequence for the simulation it was important to give a realistic view of the future. It was therefore crucial that during the simulation, the system could withstand increases in load in case the charging sequence is insufficient.

Consumption from the airport was analysed to be used in the simulations. Mean values from the last few years were considered, but it did not showcase the fluctuations in consumption in a good way. High and low peaks where flattened, loosing the natural variations. It was important to include peaks in the simulation as this is the times it is most important that the system works. Some other methods were considered, but without luck in creating a representative consumption graph. It was therefore decided it was best to use consumption from one year. As 2020 was not representative due to Covid-19, 2019 was used.

### 11.1.1 Step 1 Test Arena

Step 1 is mostly two seat test planes, with a few larger ES-19. Five to six planes are charged per day, varying between fast charging and slower charging. Step 1 is a presumed test arena for electric aircrafts in Nordic climate.

Both Åre and Östersund are seen as winter destinations, and other tourist traffic and big happenings are also centered around this season. This is also the season where the test arena will be busiest in relation to colder weather. It is likely that the airport and surrounding businesses will get increased revenue. Arjeplog, a test location for the car-industry, gets over 69 000 guest-nights during winter every year due to car developers. A similar situation might occur in Östersund.

The grid subscription is set to 1000 kW and can in combination with two batteries withstand this load in both MATLAB and PSS. The simulation in PSS can withstand a 7 percentage point higher load increase than MATLAB. This is most likely due to optimisations in the microgrid controller in PSS.

The peak load in this period is 35 % higher than grid subscription. An increase in grid subscription of at least 1380 kW would be necessary if there was not established some form of energy storage. This scenario would have a electricity cost up to 4.4 % higher than a system with BESS, as well as a higher subscription fee.

In MATLAB the cost of electricity is 2.2 % lower than in PSS. This is a result of the charge and discharge limits set in the simulations as the microgrid controller in PSS uses the batteries less to keep them healthier.

The sensitivity analysis researched the impacts a PV system could have if installed in step 1. It showed that it was not possible to reduce the number of batteries. The cost of electricity would be reduced and earlier PV installation would therefore benefit costs. Since the number of batteries was the same, it would not have significant impact on total project results.

### 11.1.2 Step 2 Airborne Shuttle Traffic

In step 2 the charging demand for the planes has increased. The new charging sequence is part of the public transport system with scheduled departures. Unlike the test arena, commercial operation has greater demand for accuracy in departure times. Therefore it is very important that the power supply is reliable, and that enough power is available at all times. The grid subscription is still set to 1000 kW. The peak load is 130 % higher than what the grid subscription can tolerate, energy storage is therefore necessary.

Using the planes as airborne shuttle traffic requires infrastructural developments at both Åre Östersund airport, and the other stops on the route. It requires a boarding and disembarking area that is not behind a security checkpoint. All stops need a runway, but it does not need to be as long as a conventional airport runways. A successful public transport system could increase number of passengers in the airport area. This could lead to increased income from cafes, kiosks, and other services like buses and taxis.

A PV system is installed in step 2. It contributes to covering loads at the airport, in addition to selling excess energy to the grid. The distribution of electricity from PV in MATLAB is 59 % for charging planes, 40 % for charging batteries and remaining for sale and covering consumption at the airport. PV reduces the annual electricity cost by 6.9 % in MATLAB and 9.4 % in PSS. This is beneficial for self sufficiency and economic savings.

Four batteries are added in MATLAB. New batteries lead to the highest CAPEX for the project in this step. When using the same inputs and number of batteries from MATLAB to the energy system simulated in PSS, the system runs without blackouts. With further testing, the system in PSS could work with one less battery pack in step 2 in the simulation with PV installed. However the system with one less battery could not withstand an increase of load, indicating that the system should install one extra battery for security of supply and flexibility. Apart from this, the system could withstand a great deal increased load, meaning that the system is stable. This is important considering there are many uncertainties with power demand, quantities of planes and the degree of energy storage.

Simulations in MATLAB and PSS shows high SoH values after five years of operations. The batteries from step 1 has, by the end of step 2, been in operation for ten years. They have reached EoL in regards to time but have a high SoH of over 90 %. Mean SoC from figure 10.5 shows a high mean SoC of about 75 – 78 % in MATLAB, and 55 % in PSS. High values are an indication that the batteries can be used more, and for a longer time. This was tested by increasing load. The system could withstand load increases of 3.0 % in MATLAB both with and without PV, and 12 % without PV in PSS. This is good for the security of supply of the system.

### 11.1.3 Step 3 Larger Electric Planes

In step 3, the loads at the airport are heavily increased with implementation of larger electric planes with longer flight range. Accuracy in departure time is important and turn around times are shorter. This leads to more fast charging, and a bigger stress on the grid. The grid subscription is increased to 5000 kW and PV is still in use.

This step requires constant use of electricity and is illustrated by almost 100 % PV distribution on charging of batteries and planes, as seen in figure 10.7. The difference in electricity cost shows that PV has smaller impact on electricity price with 4.2 % saved in MATLAB and 2.7 % in PSS.

Even though the batteries installed in step 1 in PSS has a set EoL of 10 years, they are not disconnected from the system because SoH is over 70 %. This results in a longer lifetime before the batteries are disconnected. The batteries can be used for a longer period than assumed and can contribute to reducing the total number of batteries installed later. OPEX will be a cost for more years, but this is a low cost compared to a new battery.

The largest loads are 6.3 % higher than the grid, lower than in step 2. Less batteries are needed to cover all loads. In MATLAB four batteries from step two are used. Only two are needed to cover all load, and the other two are used as emergency power supply. Two batteries can cover a 3.0 % load increase. At the end of step 3, the batteries have a SoH of 80 %. Resulting in having about one third of the lifetime left.

In PSS all batteries are in use and the system can withstand a large increase in load of 19 and 24 %, with and without PV. The system with PV has one less battery, and therefore tolerates less load increase. In addition the SoH of the batteries is very high at 97 % as stated in table 10.9. This means that the batteries can be used for a longer time. Since CAPEX of batteries is very high, PSS evaluates cost of using batteries versus price of grid over time. The high SoH indicates that PSS evaluates that mostly using the grid is the best economic choice as illustrated in the sankey diagram in figure 10.2 and D.3. If CAPEX of batteries was lower, PSS might utilize them more.

The grid subscription might not be set directly from 1000 kW to 5000 kW. A correlation between number of batteries and size of grid subscription is found in figure 10.4. Number of batteries can be decreased over time while grid subscription is increased using a model similar to the figure. Less batteries mean less investment costs. The grid subscription cost does increase, but much less than battery investment cost. However, electrification of other transportation means and equipment at the airport can increase electricity demand, requiring energy storage for operation.

Step 3 is the last step of the simulation in this thesis. The future after this is uncertain in regards to energy demand. The emission free aviation field is in fast development, and a new evaluation is needed to calculate the energy demand in the future. The replacement of international commercial airplanes will most likely not be fully electric, but presumably hybrids. The capacity of the national and regional grid in Sweden is also in need of improvement and will most likely be upgraded in the future to meet the growing power demand. An increase in power grid capacity might lead to less demand for BESS.

### 11.1.4 Plane Charging Sequence

The charging sequence of planes used in the simulation are an estimation, based on conversations with the leaders of Green Flyway. At this stage it is not possible to know if the chosen patterns are realistic. The development in the industry is hard to predict. An important question is if the plane departure and charging sequence should adapt to demand, or if the demand will change based on the plane departures.

Electric planes that need to charge can have a longer turn-around time than traditional planes. In addition, electrical grids might not be dimensioned to fit the power necessary to fast charge the planes. A balance between what is possible and what is desirable needs to be evaluated. Additionally the number of passengers wishing to travel may increase when airlines can promote emission free travel.

If commercial routes today would be replaced by electrical planes, the number of departures would increase as the planes are significantly smaller. Electric planes have limitations regarding range and seats. All-electric planes are most applicable at smaller places with a shorter distance between the airports. This is optimal for the Nordic countries like Sweden, Norway and Finland with varied topology and disperse population. A lot of these routes are already flown with medium sized airplanes today.

Flights in the airborne shuttle traffic system in step 2 will travel short distances. The planes will most likely not need charging from 0 to 100 % as they are charged at other stops as well. This means that if more planes are added to the charging sequence, the system can tolerate it as long as they do not need full charging.

It was essential that during the simulation, the system could withstand increases in load in case the charging sequence is insufficient. Results from load increase tests done on the system gives in general highest load increases in PSS. From 12 – 24 % for the different steps in PSS and only 3 – 9 % in MATLAB. This is most likely because the microgrid controller can control a load increase better than the MATLAB simulation. There is a higher total number of batteries in step 3 in PSS because the batteries from step 1 still is part of the simulation. This makes the system capable of a higher load increase.

### 11.1.5 MATLAB vs PSS DE®Siemens

In PSS, several input parameters are default, while others are alternated to match the MATLAB simulation. Some built-in values and commands can not be accessed by the user of the program and it is therefore difficult to know how these affects results. All MATLAB inputs are known and chosen to fit the simulation, and it is therefore easier to have control over results from the MATLAB simulation.

The differences in flexibility in the two softwares are most likely because of optimization in priorities and limitations in the systems. The microgrid controller decides when to charge and discharge the BESS, and prioritizes components in relation to what is economical and technological beneficial. These actions were done manually in MATLAB.

The microgrid controller in PSS prioritizes to keep the BESS healthy, mainly because of the cost difference in importing power from the grid and replacing the BESS. The simulations provides a SoH of all the batteries so high that the BESS are not phased out after 10 years. This means that in step 3 there are five and six batteries in addition to the large grid subscription, which explains how the system can withstand almost 25 % load increase. As seen in the sankey diagram from PSS for step 3 in appendix D, there is minimal amount of energy that flows through the batteries.

**Challenges with PSS DE®Siemens**

One disadvantage with PSS is that it is not possible to know all the input values for all components. This makes it hard to know how and if these values affect the results from the program. In addition, the program is still new and can have unknown bugs. This includes the lifetime of the batteries, where they were not removed after ten year. Even though it was set as lifetime.

The built-in values that are not accessible is a large uncertainty in PSS, especially in the economic assessment. The NPV in MATLAB was calculated based on Avinor's discount rate. In PSS, the discount rate was one of the parameters that was not accessible by the user. The discount rate is highly important for the calculation of NPV and the results from PSS is therefore not comparable with the values from MATLAB.

PSS is a relatively new program and is still under development. It is difficult to know if differences from MATLAB results occur because of bugs in the program or lack of control on certain input values. All input values should be accessible for the user of the program in order to know how it affects the results. Feedback has been provided to the developers of the program and they were interested to know the challenges this project faced in the simulation. If the simulated system is to be extended, PSS would be a good choice if requested adjustments are made to the program. It is a more efficient program to work with than MATLAB.

## 11.2 Components

Components include energy storage, PV and various inputs in the simulations. In addition to securing that energy is always available, both the batteries and PV shave the peaks in electricity consumption when the loads are high. As seen in figure 10.7 the power produced by PV is utilized to maximum potential. One advantage of PV for this system is that PV has highest production at the times of the day with the greatest consumption. The simulation in MATLAB prioritize batteries as electricity source when the electricity price is high. This means that in addition to reducing peaks at times of high loads, PV and batteries also decrease the electricity cost. The main objective of the batteries is to ensure that enough power is always available, reducing the electricity cost is also positive.

### 11.2.1 Battery Energy Storage

Northvolt Voltpack is the only source of energy storage used and the only battery type utilized in the simulation. It was chosen after recommendations from the supervisor. The airport is in Sweden, and choosing a Swedish supplier therefore felt like the logical choice. In addition, Northvolt is conscious in making batteries as sustainable as possible, and use recycled batteries to produce new ones. One advantage with batteries is that they can easily be removed, which can make them a solution both short term and long term.

Lithium ion batteries are the most common technology for large batteries and utility scale energy storage. The Voltpack uses NMC chemistry which is a very established technology in the market. LiB have a high energy density and low self-discharge compared to other battery technologies established in table 5.1. NMC is optimal for systems with frequent cycling and long lifetimes, as seen in figure 5.7. With current development, LiB with NMC is a logical choice for a BESS, but as other technologies evolve this might have to be reconsidered. The shortage of cobalt may also make NMC and other cobalt chemistry's less relevant. Companies like Northvolt works to lessen the impact of a cobalt deficit.

During the design of the stationary battery in the simulation, several factors had to be considered and others were rejected to simplify the simulation. Throughout this thesis, the self discharge of the battery, as well as its annual efficiency degradation rate, is not considered. This might lead to an enhanced state of health in simulations. In MATLAB, charge/discharge rate is implemented and provides more realistic simulations of the batteries in use. A battery can not always charge and discharge with max power, and this is important to include.

Number of cycles in the battery life is an important parameter, leading to large differences in lifetime. If assumed number of cycles in the simulation in MATLAB is set too high, the performance and lifetime of the batteries will be unrealistically good. However, if the number is set too low, performance and lifetime could be better than simulated. Increasing the lifetime of the batteries could decrease the number of batteries needed in the simulation. Figure 10.6 shows a minimum of 4000 cycles to avoid reaching EoL before the end of the simulation. When using a maximum and minimum SoC of 90 and 20 %, an average DoD of 70 % can be assumed. Based on figure 5.3, this correlates to approximately 5000 cycles, used in both MATLAB and PSS simulations.

A sensitivity analysis was done with EoL at 80 % SoH in MATLAB. With 5000 cycles the batteries reach EoL at exactly 15 years. This indicates that it is attainable to use batteries with 80 % SoH at EoL in the simulation.

Batteries are removed from simulation in MATLAB after ten years, as this is theoretical lifetime. However, in PSS the batteries are used in the simulation until they have reached 70 % SoH regardless if it exceeds ten years. The Northvolt Voltpack batteries are still in the production-phase. It is therefore not possible to know if the batteries should be removed after ten years regardless of SoH, or if they can be used longer as long as SoH is above 70 %.

All batteries used in simulations have a high SoH at the end of theoretical lifetime. This indicates that the batteries could have been used even more or longer than they are now. Batteries in combination with the grid are tailored to fit the period with the highest load, which generally is quite higher than normal operating load. Batteries are therefore overdimensioned for normal operation. The system would benefit from adding some form of cheaper energy storage to be used in the small periods in the year with very high loads. This could lead to needing fewer batteries and reducing BESS investment costs.

**Emergency Power Supply Batteries**

Blackout tests done on the system show that the two emergency supply battery packs can supply the needed power at the airport for 24 hours in both simulations. Blackout tests were done in the winter, as this is the time of the year with the highest consumption. Because of the assumed minimal use of the emergency power supply batteries, it is thought that the lifetime of these batteries can be longer, as well as work in combination with BESS. If BESS have a high SoC at the time of blackout, they can increase the supply time of emergency power to vital parts of the airport.

The blackout test represents islanded mode in a microgrid, where the system is cut-off from the external grid. With the limited energy storage and production, the microgrid is not able to function in islanded mode for a longer period of time. A larger energy production, as well as additional energy sources is needed for the energy system to operate as a islanded network.

In theory it may be best to separate emergency power batteries and energy storage batteries to keep the emergency power safe from malfunctioning in BESS components. The most optimal resting SoC of LiB is 50 %, requiring the emergency power batteries to have higher capacity to meet this demand. Another way to solve this is to connect the emergency demand to the BESS, and increase the minimum SoC to ensure emergency power demand is always available.

### 11.2.2 Solar Power System

It was important to simulate a system both with and without PV because there is a chance that PV license application can be declined due to national interest issues. The main advantage of PV production is to decrease the electricity necessary to retrieve from the grid, and secure that the batteries are charged with renewable power. All PV production is well utilized at the airport, giving a lower electricity bill. Both step 2 and step 3 utilizes the electricity from the PV installation to full extent. Under 1 % and 2 % respectively is exported to the grid. Utilizing the power instead of selling it is beneficial because the sales price for PV is lower than the power price when importing from the grid.

The annual electricity cost for the airport is 6.9 % lower with PV in step 2 in MATLAB and 9.4 % lower in PSS. A reason for the larger savings in PSS can be the use of the microgrid controller. It evaluates the most beneficial use of the PV electricity, while MATLAB has a set order of priority. In step 3, the electricity is respectively 4.2 % and 2.7 % lower with PV in MATLAB and PSS. The difference between the two softwares is minimal and the savings is less than in step 2. This is a result of significantly higher load demand, making PV production an even smaller share. Degradation of the PV system is included in PSS and not MATLAB. This is most likey the reason that the savings from PSS have been reduced with 4.0 percentage points more than the reduction in MATLAB.

PV does not have a significant impact on the simulated energy system but provides a degree of self-sufficiency and is a security energy source. To have local energy production is beneficial if a power outage occurs. It can increase the time before blackouts in periods with high production. The simulated blackout tests was performed in the winter season and showed no difference with and without PV. A PV installation could have more beneficial effects if located in an area with more sun over longer time periods and lower azimuth angles.

The PV system is not installed until step 2 in the simulation. The timeline simulated and used in economic calculations installs PV around 2030. The ongoing development within the PV industry indicates a sinking price per $W_P$, increasing panel efficiencies and smaller production degradation rate as shown in chapter 6. The production reduction from snow also varies from year to year and have a sinking trend due to global warming. This could be implemented to the installation and production in this thesis. It can be assumed that the PV system could have higher efficiency, higher production over the entire lifetime and cost less than what is included in simulations. Therefore have larger beneficial impacts on simulation and results.

**Placement of Solar Installation**

The decision to install PV in connection with Frösö Park can mean that the energy production from PV has to be shared. Because of this, the sensitivity analysis include tests where PV production is halved to see if the system still function without blackouts. The analysis shows that both simulation in MATLAB and PSS can withstand a 50 % share of PV production. The production was also doubled to illustrate a larger PV installation. The number of batteries needed could not be reduced. Both these results emphasizes the minimal effect PV production has on total project results.

Due to Covid-19, it was not possible to visit the airport and surrounding areas. This made it harder to find a fitting area for PV ground-mounted installation and the roof-mounted installation was therefore decided for this thesis. Information from Jämtkraft was provided after the simulation was complete. The surrounding area mostly consists of unprocessed ground, making ground-mounted installations possible.

Even though a roof-mounted installation at Building 90 was chosen for this thesis, a ground-mounted system is also a possibility. The ground-mounted installation projected by Jämtkraft has 84 more panels, hence 6 % higher peak power than the simulated installation. The cost for the ground-based installation is estimated to be around 3.8 MSEK, while the roof-based installation in simulations is calculated to cost around 3.85 MSEK.

The close relation between production and costs for the two installations is positive for the simulation designed in this thesis. It would not have major impacts on results if the opposite installation method was chosen, which creates a flexibility for an actual execution of the project. The largest advantage with the ground-mounted system is that it is closer to the airport and most likely do not have to split the energy production with Frösö Park.

When making a decision on roof-mounted or ground-mounted PV installation at the airport, panel type can make a significant difference on production. It can be beneficial to have bifacial PV panels with a tracking mechanism on a ground-based installation. It is more normal to install PVs with tracking in ground-mounted PV systems. Bifacial panels have larger production as they utilize reflection from the ground as well. These type of panels can increase the production of a ground-mounted installation compared to a roof-mounted, but is a larger expense as more technical panels often cost more.

### 11.2.3 Chargers and Standardization

The charger is connected to the electric vehicle by cables and a charging point. The electrical aviation field is in the beginning of the development process. Therefore, there is no standardization in charger type and power for the planes. A size of charger was chosen based on information on chargers for bigger electric cars and trucks. The actual size of the chargers might be bigger than what was chosen for the simulation. This can lead to the simulation not showing reality of the power demand for the planes. Megawatt chargers are under development, but the demand and evolution 10 to 15 years in the future is highly unsure.

When high amount of power is moving through the chargers, specifically in mega-chargers, the cables between the charger and vehicle will be quite heavy. The connection between the charger and the EV was not taken into account in the simulation, however it is an important discussion. For electric planes the solution might be hands-free charging by a robotic arm, or dividing the charging into separate cables with separate charging points on the vehicle. In some bigger electric vehicles, like ferries, charging by induction has been implemented to make the charging process easier.

Automating the charging process removes the potential of human error. This reduces the risk of malfunctions of the components in the system, and makes it safer for the staff involved. A charging standard in electric planes will also benefit the safety of infrastructure and emergency response. In case of emergency, standardization is key to having a good outcome. Emergency response personnel need clear guidelines and knowledge of specific components, and an established standard will make it easier.

The implementation of chargers, both slow and fast, will influence the infrastructure at the airport. They represent a very big part of the total load in the energy system, especially in a small airport like Åre Östersund. In step 3, if a 4 MW charger is used, it will use 80 % of the imported power from the grid, causing a significant power peak.

Charging batteries could pose a problem in Östersund, where the temperatures often are below freezing point during the winter. It is important for batteries to be charged at a suitable temperature, both for the health of the battery and for safety. The BESS at the airport will however be discharged multiple times every day and most likely not become cold between each charge. The BMS of the batteries also help regulate the temperature, and keep it from getting too cold or hot. The electric planes at the airport will also mainly either be fast charged to meet TAT or charged over night when the batteries are still warm. The batteries will need to be heated before charging if the planes have been parked for a longer period of time. The colder climate in Östersund will most likely not be an issue for batteries in daily operation.

## 11.3 Safety Considerations

Airports are considered critical infrastructure in society. This entails strict laws regarding the safety and operation of every component and service at the airport. An airport needs to have a secure power supply at all times and reliable emergency power in the event of a power outage. The emergency power needs to cover the most critical components of the airport, mainly on the airside. Safety aspects of components in the energy system must be evaluated.

### Emergency Power Supply

When Åre Östersund airport aims to have an emission free energy system, they are required to replace the diesel generators with a sustainable option. In this thesis, the diesel generators were replaced by battery packs. The battery packs delivered by Northvolt work as emergency power systems and UPS. The batteries are capable of providing instantaneous power and contains the needed capacity to run the critical components for a given amount of time. To ensure security of supply it might also be an option to not fully replace the diesel generators, but use a different and more sustainable fuel type, such as biofuel, in addition to batteries.

The battery packs replacing the diesel generators could be connected to the other BESS at the airport or be kept separate. If the emergency power batteries are kept separate they will most likely only be used if there are faults in the normal power supply. Keeping them separate ensures that the emergency power batteries are not affected by faults in the BESS. One of the benefits of keeping the emergency power connected to the other BESS is the added capacity, although the system would be vulnerable to errors while connected.

Batteries used for storing energy for emergency power supply should have a SoC of 50 %. This is to avoid instabilities within the cathode in the battery cell that can be the source of fire. The closer SoC is to fully charged condition, the larger the risk of oxygen development which can react with the electrolyte and cause fire. A 50 % SoC will minimize this risk and keep a chemically stable battery cell. When leaving the batteries at a higher SoC it will also lead to increased aging of the battery. The limited use of the emergency power batteries at a recommended rest-state will most likely result in improved lifetime, i.e. longer than 10 years.

### Battery Safety

The large changes being done at airports aiming to be more electric and sustainable leads to new safety considerations needing to be made. Fire has always been a risk at airports and in the transport sector. As new components are introduced, new adapted safety measures must be made. Both charging of electric planes and batteries provides a risk of fire. It is a concern discussed by several large contributors in the industry and will be handled in line with future development.

It is important to have a common standard for charging and fire safety concerning electric planes in order to be able to avoid destructive fires. An important measure is to replace power cables and other electric components if damaged or worn out. If a battery has a healthy SoC, the only components in the battery that is flammable are the electric components and the electrolyte. Quarantine routines are important to prevent fires in batteries from flaring up again. Various technologies and methods are being researched to detect fire in a battery before it ignites and minimize the extent of damages caused by fire. The BESS researched in this thesis is a large battery pack, hence an increased fire risk.

### Solar Cell Safety

A PV installation in connection with the airport can have safety issues that must be taken into account regarding EMI interference and reflection on pilots. There is a minimal probability that EMI interference from PV systems occurs, but if it happens it can have serious consequences on airport security and human- and system safety. The only EMI risk in a PV system is the inverter. In order to reduce the possibility of EMI interference from PV inverters, there has to be a distance above 46 m from the placement of the inverter to critical components. The placement of the inverter is decisive for the airport to consider when installing PV. Both suggestions on roof- and ground-mounted installations are located at further distances from the airport, which provides several opportunities for inverter placement.

Reflection from PV can be a safety issue when it comes to flash blindness for pilots during final approach. Anti-reflecting coating reduces the risk of reflection, but does not abolish it. An angle above 25° from final approach is therefore considered when choosing the location for the PV installation. The possible location of both roof- and ground-mounted installations is illustrated in appendix A. The installation in simulation was set to Building 90, south of the airport. This reduces the possibility of reflection because the panels face south and has a high slope of 49°. The ground-mounted installation is located north of the airport runway and would therefore have a larger risk of reflection.

## 11.4 Economic Assessment

In the simulation in MATLAB a boundary between high and low electricity price was set to determine when to charge/discharge the BESS. In actual operation a microgrid controller needs to make the assumptions of what is a high and low price. A method analysing the electricity price every hour five days prior, gives a good indication of the electricity price the following 24 hours. The difference in the electricity cost from tables 10.5, 10.8 and 10.10 indicates that PSS, with a microgrid controller, uses different boundaries between high and low prices.

Electricity price will increase in the future. Sweden is planning a big expansion of the national power grid to meet the growing demand, and in addition the number of international cables are increasing. This will lead to increased energy costs, and make self-sufficiency more lucrative. Making energy storage and peak shaving much more important to keep costs low.

Both PV and battery technology are rapidly developing. Prices have dropped and will presumably continue to drop in the future. Investment in energy storage and production has a big impact on the profitability of this project. Decreasing prices can lead to more investment incentives. The rate that prices are dropping on sustainable technology makes it more profitable to invest in new technologies as well. Throughout the timeline set in this project, there might be other technologies that will be more suitable for an airport energy system e.g. hydrogen.

Standard deviations are included in all costs and economic calculations. They represent a insignificantly small share and are therefore excluded from all results.

### Economics from Simulation

Net present value is positive for simulations both in MATLAB and PSS, giving profitable economic investments. It is 27 % higher with PV installation in MATLAB, showing that the savings in electricity costs has been beneficial. The sensitivity analysis shows that the tested reductions of income results in negative net present value, except a removal of the fixed hourly cost of 75 SEK/h. Trends from the sensitivity analysis applies for both economic parameters.

The payback period of the project in MATLAB is close to 16 years, with a small difference of 0.6 % for the system with and without PV. The project reaches break-even point early with several years left of the project lifetime. If batteries were installed in step 3, it could impact the payback period because it is a large investment. Another reason for an early break-even point is large incomes from planes charging. In the sensitivity analysis, a income based on spot price creates the largest deviation from simulation with up to 45 % longer payback period. The reduced energy price of 1.50 SEK/kWh also results in a payback period longer than project lifetime.

Factors that can impact the economic results and the profitability of the project that is not considered in the simulation is costs of cabling, substations, chargers, etc. Uncertainties regarding ownership of chargers leads to this cost not being evaluated in this thesis. In addition financial support from sponsors and government is not included. This type of renewable project working on electrifying an industry could get financial support from multiple companies and other institutions. It may lead to greater annual income and reduced investment costs and could have a major impact on the profitability of the project. The value of the financial support is very uncertain because the development is in its early stages and therefore not included in this project.

The price per seat is still much lower for electric planes, with the charging price used in the simulation, than for planes in use today. This means that the price chosen might be reasonable. It is important to note that jet fueled planes have a longer range. A shorter range could lead to other costs not considered in the thesis.

### Residual Value of Components

The financial results in MATLAB are calculated using a residual value where PV has a sale value of 33.3 % of purchase cost. The batteries have reached their EoL in the simulation and therefore has no residual value. In PSS the batteries installed in step 1 has a residual value of 61.7 %. The batteries installed in step 2, both in combination with PV and without, has a residual value of respectively 63.0 % and 63.1 %. It is not realistic to expect to sell the components, but is added as residual value to compensate for the overlapping design of the simulation and the remaining lifetime.

The residual value have a big impact on the NPV of the project. Battery investment is the most expensive part of the project. The batteries in MATLAB with no residual value could in reality be sold to someone who can use the batteries further. This means that having a residual value like in PSS could be more realistic. It would make the profitability of the project more flexible to less income. In PSS there is no residual value for PV. The program does not give an explanation for this, but it is thought that this comes from the PV system being harder to move and use other places without damage.

### 11.5 Life Cycle Assessment

In Östersund the local power company Jämtkraft advertises with 100 % renewable energy. The LCA performed uses the national energy consumption mix in Sweden at 52 g $CO_2$-eq/kWh. This is a low carbon share compared to the rest of the world. Most studies done on LCA of batteries are done in countries with a higher carbon footprint than Sweden. In the assessment of Östersund 50 % of total emissions is from production, and the remaining from use phase. Numbers concerning battery production is based on production in the US, and can be lower as Northvolt has a big focus on creating environmentally friendly batteries. The $CO_2$ emissions from the use phase in each step increases as more energy is stored in the batteries.

The mono-Si PV used in this thesis has a 3.5 percentage points lower efficiency than the mono-Si PV from 2020 researched in the LCA chapter. This can most likely lead to higher carbon footprint than calculated value of 9.42 tonne $CO_2$-eq from the theoretical mono-Si PV system. However, technology development indicates that PV efficiencies will increase in the years to come. PVs are not installed until step 2, meaning the efficiency of the installed system could be higher than assumed.

### 11.6 Future in Emission Free Aviation

Reducing GHG emissions is essential in slowing global climate change. The aviation sector is responsible for 2 % of global GHG emissions today. This number is expected to increase to 15–27 % by 2050. High and upper-middle income countries are responsible for 90 % of aviation emissions. Switching to clean fuel alternatives is important to reduce these emission. Sweden aims to have fossil free domestic aviation by 2030, while Norway aims for 100 % electric domestic aviation by 2040. Electrification of the aviation sector has the potential to cut major parts of both global and local aviation emissions.

The future in emission free aviation will most likely be based on more than one type of fuel. Electric planes, e-fuel and hydrogen are all alternatives that are being researched and developed. Therefore, it is important that airports have the infrastructure to supply all fuels in demand. This requires extensive planning and organization. It is expected that the first commercial all-electric plane, ES-19, will depart from Åre Östersund airport in 2026.

The transition to electric airplanes will result in discounts and exemptions from certain taxes for the airlines. Though this leads to less income for the airports, it will most likely be replaced with a charging fee. This results in income for the airport, and also reduced costs for airlines. The transition to emission free aviation has the potential to become economically beneficial for both airports and airlines.

An increasing electricity demand generally applies to large parts of the world. The issue the airport is facing with limited grid capacity is relevant to many locations and is not only limited to this airport. The system designed in this simulation is a general system that can be applied to many other airports. It can easily adapt to inputs from other locations, like grid- and battery capacity, PV production, airport consumption and plane charging demand.

The system is most relevant for small airports because it is limited how much energy can be stored in the batteries without the cost being too high. Bigger airports with a bigger flight network might need additional electricity sources. For Åre Östersund airport PV was not a big part of the electricity production, at 4.8 % for the total project lifetime. For airports in areas with more sun and less snow this could have a greater impact on both electricity cost and income.

Electric vehicles have less noise pollution, which can also make airborne shuttle traffic relevant in cities and other locations. With the correct infrastructure the electric airplanes could take off and land closer to city centers, making it relevant to a large part of the population.

## 11.7 Further Work

The rapid development and research within the aviation field makes further work important. The new generation of sustainable and electric airplanes may differ from the components used in this thesis and require more or less power, or other forms of energy storage. At the moment there are no standards in charger type and power. Using more accurate information and dimensioning to simulate the charging of the airplanes will further improve the results gained in the simulation.

There are multiple projects working on creating a charging system using swappable batteries. If a standard size is decided, it could lessen the impact on the energy system. The use of swappable batteries makes it easier to charge during periods of lower loads. It also minimize the use of rapid charging, which is important for the grid health. This may benefit the system needing less grid upgrading and energy storage, which would be financially positive.

Because of the limited available information and inputs, the simulations are completed on an hourly basis. To better simulate the rapid charging of the planes and response time of the components, it would be better to simulate in minutes, seconds or shorter. This would make simulating short turn around times for the planes easier, with more information on the consequences of this.

Further work would also include a deeper analysis in the delimitation of this thesis. There are a number of delimitations made in the simulation, and further work should include some of these limitations to make an even more accurate system. For instance, the economic specifications of components like chargers and other elements are excluded, but could influence the profitability.

Only one type of battery was used in simulations in this thesis. Further work should also consider and evaluate other battery options. Both considering performance, but also in regards to emissions in relation to production and recycling. In addition, other sources of emergency power supply should be considered, like gas turbines, fuel cells and flow batteries.

In periods with irregularly high peaks, i.e. the peaks in the winter periods in the simulation, an alternative energy source could be implemented. Further work could benefit from researching how much this type of peak affects the energy storage system. Generally high SoH values indicate that there is a possibility that fewer batteries could be needed without the peaks. Adding some form of cheaper energy storage, used in the small periods in the year with very high loads, could financially benefit the system.

In the economic assessment, the airport with Green Flyway, is responsible for the costs of all new components. In other electrification fields, other stakeholders are in charge of installing and operating the charging system. If this is done at Åre Östersund airport, it could lead to less financial uncertainty for the airport. Different business models can be considered.

To create a fully emission free airport, other transportation vehicles at the airport should also be electrified. This includes e.g. busses and cars, pushback tugs, de-icing trucks and snowplows. These vehicles are omitted in this thesis, but is essential at an airport. To fully understand and make the transition to a sustainable and emission free airport, every component needs to be included in the analysis. In addition, the increasing number of EVs on the road could require more chargers in the airport parking areas.

**Hydrogen**

Hydrogen is set to become an important part of the future, but was not a part of the simulation. This was chosen after conversations with Jämtkraft. Jämtkraft's plan for the future of hydrogen in the area shows that production on sight at the airport is currently not applicable. When the planned electrolyser in the area is in operation it is possible to have hydrogen delivered to the airport. This makes it possible to both fuel airplanes and use fuel cells as energy carrier, emergency power supply and other uses at the airport. This requires infrastructural developments at the airport. It is not possible to know how hydrogen can be implemented at airports, both in regards to safety and space.

In regards to safety, hydrogen as fuel have many benefits compared to traditional fuels. As hydrogen is the lightest element, it rises in the case of a leak instead of pooling on the ground, leading to less fire hazard in the vehicle. A hydrogen vehicle also have various sensors for detecting leaks. As the technology develops it can become more valuable both for airplanes and energy storage, and further investigations should be done.

## 11.8 Summary Remarks

Future electrification of the aviation industry will entail considerable changes in terms of electricity demand and infrastructure of airports. As charging of electric planes is implemented, electricity consumption at the airport is expected to increase, mainly with regard to high power peaks when charging. This new industry is energy intensive, and demand can be higher than available power. This is the case at Åre Östersund airport, where simulations show that energy storage is necessary to ensure security of supply. The simulations were performed in MATLAB and PSS and provide similar technical results. In this way, the simulations validate each other. PSS have some built-in values and commands. It is hard to know the extent these affect the results.

As a test arena, Åre Östersund airport must have sufficient energy supply and be adaptable to various technologies in aircraft development. With the implementation of ES-19 as airborne shuttle traffic, punctuality is essential as commercial operations have greater requirements for accuracy in departure times. This requirement also applies for larger electric commercial airplanes expected in the future. Reliable and sufficient power supply is crucial for all stages in aviation development.

BESS has the potential to act as a harmonizing intermediary in the energy system at the airport and reduce power peaks. It is a large investment cost, but necessary to compensate for limiting grid subscriptions. In step 2, the loads are 130 % higher than grid subscription. This is a type of system where energy storage is necessary to cover all loads. This results in the highest frequency of battery use in this period, working in collaboration with grid and PV. With the large grid subscription increase in step 3, the need for energy storage is smaller. With the implementation of megawatt-chargers, BESS ensures that the rest of the airport has power available.

The batteries in simulation have high SoH and SoC values, indicating a well functioning system. This includes using batteries as emergency power supply, where blackout tests shows promising results. It is important that the energy system at an airport functions during a blackout, where faults in operation could be fatal. To ensure security of power supply it might also be an option to not fully replace the diesel generators, but use a different and more sustainable fuel type in addition to batteries.

The PV system contributes with renewable energy supply to daily operations. It is a source of self sufficiency at the airport and have low GHG emissions. Simulations indicate that PV production has minimal impact on project results, both regarding energy consumption and economic assessments. Even though energy from the PV installation is fully utilized at the airport, it has minimal impact in periods with high load demand. However, it is an industry in rapid development where trends illustrate an increased efficiency. This results in higher energy production in a future scenario.

Based on economic assessments, the most profitable solution is to maximize grid import and implement energy storage to harmonize with other components. With limited grid capacity, energy storage is vital. With the integration of BESS and PV at the airport, the energy system functions as a microgrid. A microgrid controller prioritizes and optimizes the operations of the different components. Based on the limited energy production, the airport is not able to be islanded from the external power supply. The energy system at the airport is dependant on energy storage, and can only be islanded for small periods of time at normal operation.

Limited grid capacity is a problem for many other locations. The implementation of energy storage is therefore highly relevant for airports transitioning to emission free aviation. The simulation done in this thesis is general and can be implemented other places, especially small scale airports. It can however be improved when more research and development is completed, to give more accurate results. The limitations in this thesis are mainly a result of limited data and minimal existing information on the subject. The evolution in this field is rapid and more suitable technologies can be introduced, both in regards to airport infrastructure and aircrafts.

# Conclusion

Charging of electric planes entails high power peaks, making electrification of aviation an energy intensive industry. Simulations of the energy system were performed in PSS DE®Siemens and MATLAB and provided similar technical results. With fast charging and high power demand, local energy storage is necessary to ensure security of supply. With the implementation of BESS and PV, the energy system works as a microgrid.

Åre Östersund airport has the potential to be an international test arena for electric aviation in arctic climate. It has to be ready to accommodate medium and large commercialized electric planes in operation. Reliable and sufficient power supply is crucial for all stages of electric aviation development. The implementation of medium and large electric airplanes are relevant to many other airports. Simulations completed in this thesis can be performed at other locations, but is most suited for small airports with limited grid capacity.

The energy storage system works to harmonize the key components at the airport. It is a large investment, but necessary to meet the power demand of large electric planes and fast charging. Results from simulation show that the amount of energy storage needed is highly dependant on the power available from the grid. In the airborne shuttle traffic scenario with high power demand and low grid subscription, the system was dependant on up to six battery packs to operate. The following scenario, where larger electric airplanes was implemented, had significant increase in grid subscription and operated without additional battery investments. Based on economic assessments, the most profitable solution is to maximize grid import.

PV production is beneficial for the self sufficiency of the energy system, but has minimal impact when power peaks are high. A disadvantage with PV is the small production in the time of the year with the highest energy demand. The PV system only covers 4.8 % of the total energy consumption at the airport over project lifetime.

Batteries are also used as uninterrupted power supply and emergency power supply. Blackout tests shows that the batteries works well for approximately 24 hours. For blackouts longer than this, it might be unavoidable to retain the generators with a sustainable fuel.

Technology available today provides various opportunities and combinations for energy storage and production to ensure security of supply at airports. Implementation of energy storage is highly relevant for airports transitioning to emission free aviation. As the technologies develop and more information is available, a more accurate simulation can be preformed. In conclusion, a sustainable energy system at Åre Östersund airport is fully realizable and an important step toward emission free aviation.

## Recommendations to Green Flyway and Åre Östersund Airport

In this thesis, the evolution of electric airplanes at Åre Östersund airport is illustrated in three steps. The first step is Åre Östersund airport as a test arena, followed by airborne shuttle traffic of Heart Aerospace ES-19. Lastly larger electric airplanes are introduced in the energy system.

As a test arena in step 1, the airport is assumed to test smaller electric airplanes, like Phinix already in use and ES-19. Today, the energy system at the airport can tolerate both fast and slow charging of small two seat planes. However, with the implementation of ES-19, the power demand will increase. Depending on the charger size, the power demand will be higher than grid subscription and energy storage is needed. With two battery packs as energy storage, the system could tolerate the load of the 1 MW charger and airport consumption.

The airborne shuttle traffic of ES-19 in step 2 has greater need for energy storage. The simulation uses the same 1 MW charger as step 1, but includes periods where two planes are charged simultaneously. Assuming that the grid subscription has not increased from step 1, the power demand is substantially higher than what the system can withstand. An additional four batteries are installed to cover this demand in the simulation.

In the last step, even bigger electric airplanes are tested and certified for commercial flight. This results in a significant increase in power demand, especially during fast charging. By the time the larger planes are introduced, it is expected that improvements in the Swedish power grid have been made, making the grid more equipped to meet demand.

By simulating different steps in aviation development, it is clear that energy storage is necessary to provide security of supply at all times. Grid subscription is decisive regarding number of batteries needed in the energy system. Upgrades of the grid is important to reduce large investment costs of energy storage, but it is beneficial to have batteries to peak shave and optimize operations.

It is crucial for Green Flyway and Åre Östersund airport to be updated on development to design a successful energy system at the airport. This includes evolution within the aviation industry, development of charger types and local grid upgrades. This information is essential to understand future power demand and necessary energy storage at the airport.

As a test arena, it is important that other sustainable fuels are accessible at the airport at all times. This includes hydrogen and e-fuels. Constant dialogue with fuel developers is crucial to have a stable line of supply of all fuels. Dialogue with airlines and airplane developers is also important to create a energy system and charging infrastructure prepared for commercial flights.

As the Green Flyway project is finished in the autumn of 2022, new projects must pick up where Green Flyway left off. Constant cooperation between airplane developers, airlines and airport operators, as well as surrounding facilities and researchers, is key to a successful transition. While Green Flyway is creating a basis and foundation for electric aviation in Sweden and Norway, it is important to maintain the momentum after the project is finished.

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# A Installation of Solar Cells

The location of Building 90 and the possible ground-mounted installation is shown in figure A.1. The location is shown in relation to Åre Östersund Airport, the runway and Frösö Park Arena.


**Figure A.1:** Building 90 and ground installation in relation to the airport. Edited from original.[110]

The peak power of a single GCL Monocrystalline is calculated using equation 6.1 and the result is shown in equation A.1. $\phi$ is not included in the calculations because it is a component included by PVGIS later.

$$P_{W_P} = (1.64m \cdot 0.992m) \cdot 0.19 = 0.3097kWp \tag{A.1}$$

Building 90 has an area of $6600m^2$. With a distance of 3 meters between each row and the panels mounted horizontally, there is space for 1320 panels. This creates a total peak power of 408.8 kWp for the installation, shown in equation A.2. 408.8 kWp is the only calculated value used as input in PVGIS.

$$P_{W_{P tot}} = 0.3097kWp \cdot 1320 = 408.8kWp \tag{A.2}$$

The total weight of the installation is calculated in equation A.3.

$$m_{tot} = 18kg \cdot 1320\text{p}anels = 23760kg = 23.76tonne \tag{A.3}$$

# A Installation of Solar Cells

### Description of PVGIS correcting factors

PVGIS is used to extract hourly solar radiation data and with several correcting values. Shallow-angle reflection corrections include the light reflected from the PV surface without entering the module. This factor increases at sharper irradiation angles.

Corrections based on the effect of changes in the solar spectrum takes the solar wavelengths into account. PVGIS adjusts to the spectral sensitivity different PV technologies have, variations throughout the day and impact of cloud cover. One of the PV technologies in the program is crystalline silicon. Corrections based on degradation with age and system losses include losses in cables and inverters and design variations on modules.

Module temperature can rise above the local air temperature when the sun shines on it, and is therefore an important correction. PVGIS also considers the cooling effect wind can have on module temperature.

In addition to this, corrections are made based on how PV power are dependent on irradiance and module temperature. It includes factors from outside conditions that effects the efficiency, i.e. that PV efficiency decreases with increasing temperature. Efficiencies are often calculated in standard conditions at factories, which may result in a lower efficiency in use.[155]

# B Flow charts

Flow charts based on code and simulation in MATLAB is presented in this attachment. Table B.1 shows abbreviations and explanation of parameters used in simulation. Figure B.1 shows the flow chart when no planes need charging. Figure B.2 shows the flow chart when planes need charging.

**Table B.1:** Abbreviations used in flow charts.

| Symbol | Explanation | Unit* |
|---|---|---|
| $CDP$ | Charge demand plane | [kW] |
| $EP$ | Electricity price | [SEK/kWh] |
| $SoC$ | State of charge | |
| $SoC_{max}$ | Maximum state of charge | |
| $P_{AS}$ | Power available at simulation start | [kW] |
| $P_{AF}$ | Power available at simulation finish | [kW] |
| $C_{Bmax}$ | Maximum battery capacity | [kW] |
| $P_{Bchr}$ | Battery charge power | [kW] |
| $P_{Bdis}$ | Battery discharge power | [kW] |
| $P_{cons}$ | Power consumption | [kW] |
| $P_{grid}$ | Grid subscription power | [kW] |
| $P_{sun}$ | Solar power | [kW] |

*Empty cells are dimensionless

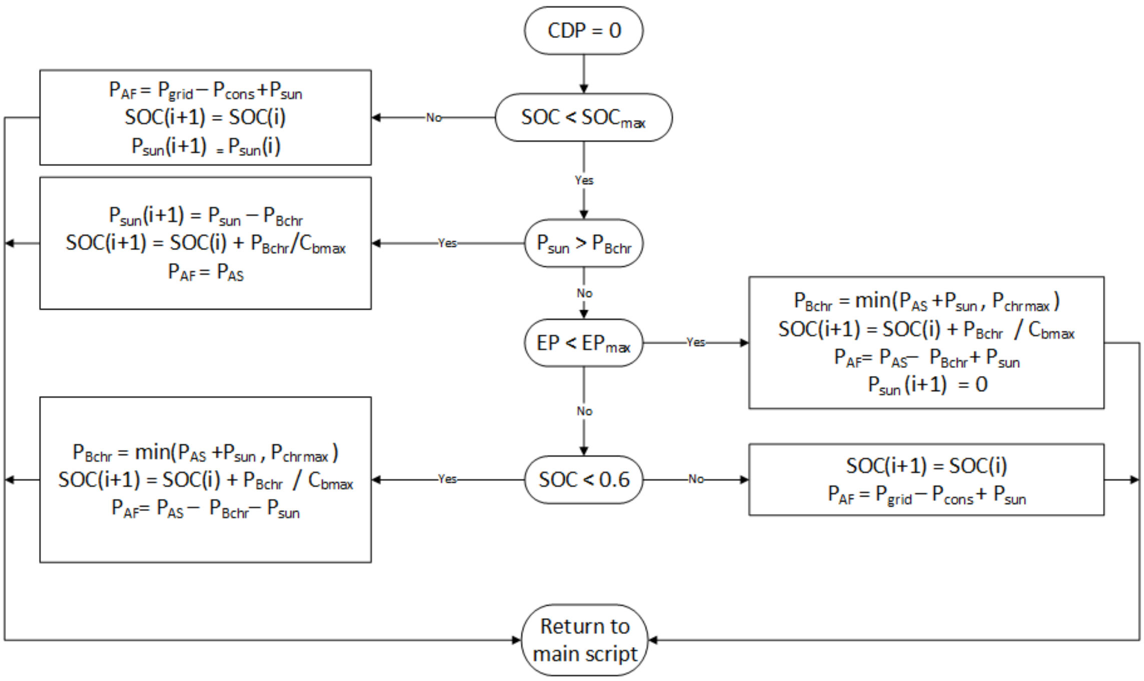


**Figure B.1:** Flow chart for MATLAB simulation when no planes need charging.

# B Flow Charts

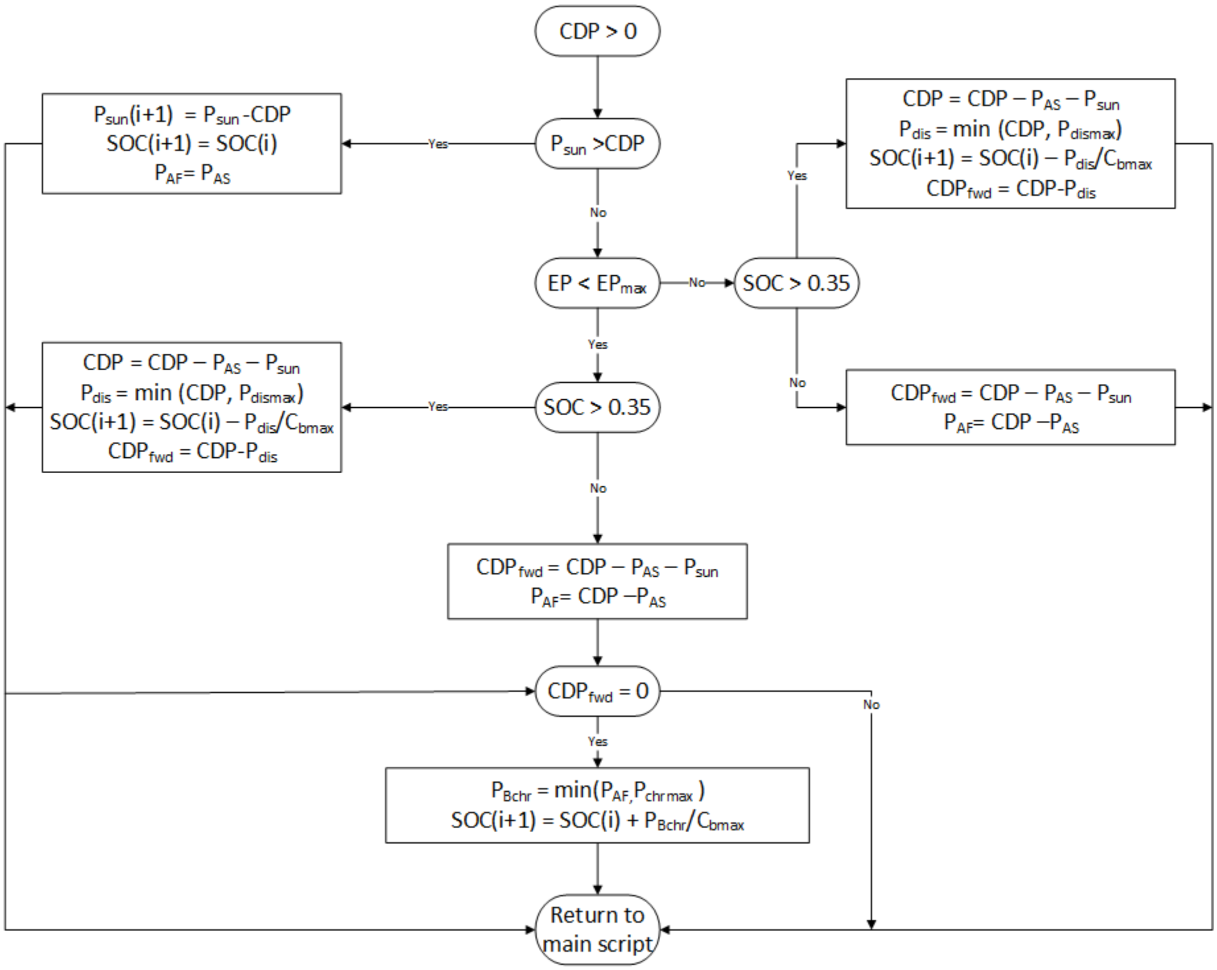


**Figure B.2:** Flow chart for MATLAB simulation when planes need charging.

# C CAPEX and OPEX

CAPEX and OPEX in each step is presented in this attachment. BESS is the batteries installed for daily use. EPS batteries are emergency power batteries only used if a blackout occurs. OPEX for batteries are for all installed batteries. The grid subscription fee is calculated based on 337 SEK/kW. PV is included in all tables, but has to be withdrawn from the total sum for the scenarios witout PV.

Table C.1 and C.2 shows CAPEX and OPEX in step 1. Grid subscription is 1000 kW. PV is not included in step 1, hence not included in the tables.

*PV is not installed in all scenarios.

**Table C.1:** CAPEX Step 1

| **CAPEX Step 1** | | | |
|---|---|---|---|
| **Components** | **Size** | **Price per** | **Total price** |
| BESS | 2 | 10 535 000 SEK | 21 070 000 SEK |
| EPS battery | 2 | 10 535 000 SEK | 21 070 000 SEK |
| **Total** | | | 42 140 000 SEK |

**Table C.2:** OPEX Step 1

| **OPEX Step 1** | |
|---|---|
| **Components** | **Total price** |
| Total battery | 40 000 SEK |
| Grid subscription fee | 337 000 SEK |
| Grid fixed fee | 15 550 SEK |
| **Total** | 392 550 SEK |

# C CAPEX and OPEX

Table C.3 and C.4 shows CAPEX and OPEX in step 2 where PV is installed. Grid subscription is 1000 kW. No EPS battery is needed to be installed in step 2 because of lifetime of 10 years.

**Table C.3:** CAPEX Step 2

| **CAPEX Step 2** | | | |
|---|---|---|---|
| **Components** | **Size** | **Price per** | **Total price** |
| BESS | 4 | 10 535 000 SEK | 42 140 000 SEK |
| PV purchase* | 409 kWp | 2.41 SEK/Wp | 985 690 SEK |
| PV installation* | 409 kWp | 7 SEK/Wp | 2 863 000 SEK |
| **Total** | | | 45 988 690 SEK |

**Table C.4:** OPEX Step 2

| **OPEX Step 2** | |
|---|---|
| **Components** | **Total price** |
| Total battery | 40 000 SEK |
| PV O & M* | 30 000 SEK |
| Grid subscription fee | 337 000 SEK |
| Grid fixed fee | 15 550 SEK |
| **Total** | 422 550 SEK |

Table C.5 shows OPEX in step 3. Grid subscription is 5000 kW. There are no batteries or PV investments made in step 3 and therefor not a CAPEX table.

**Table C.5:** OPEX Step 3

| **OPEX Step 3** | |
|---|---|
| **Components** | **Total price** |
| Total battery | 40 000 SEK |
| PV O & M* | 30 000 SEK |
| Grid subscription fee | 1 685 000 SEK |
| Grid fixed fee | 15 550 SEK |
| **Total** | 1 770 550 SEK |

# D Sankey Diagrams for Step 1, 2 and 3

An overview of the total distribution for each step from the simulation in PSS is shown in sankey diagrams in this attachment. Figure D.1 shows the sankey diagram for step 1. It shows that in step 1, 3.0 % of total energy input is stored in batteries.


**Figure D.1:** Annual sankey diagram from PSS-DE®Siemens showing step 1. Edited from original.[80]

Figure D.2 shows the sankey diagram for step 2. Annual PV production sold to the external grid in step 2 is 5.5 % while 10 % of total energy input is stored in batteries.

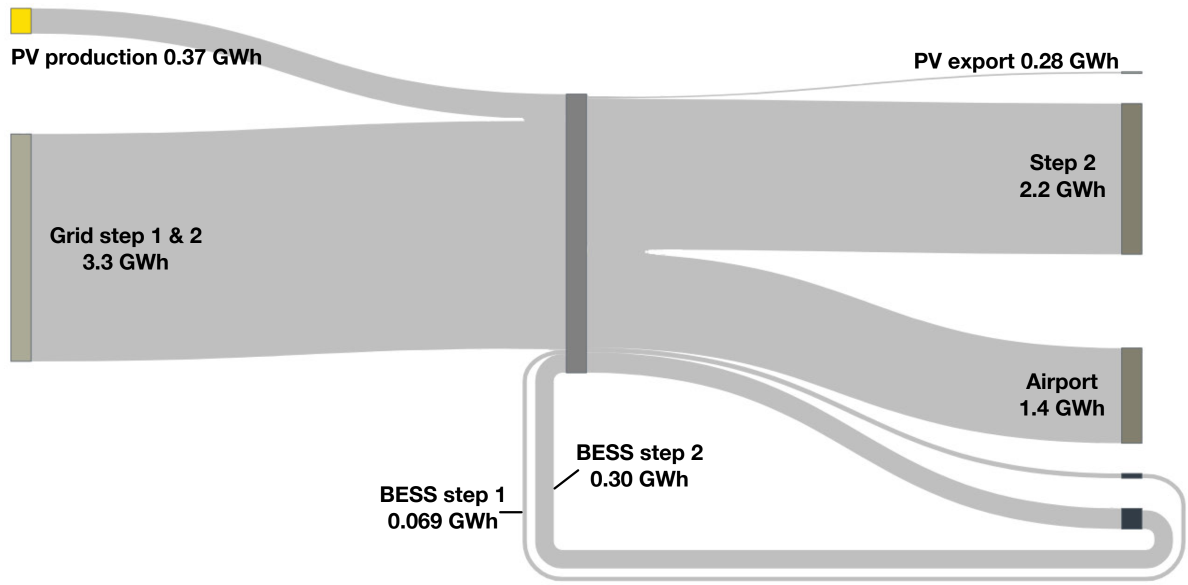


**Figure D.2:** Annual sankey diagram from PSS-DE®Siemens showing step 2. Edited from original.[80]

# D Sankey Diagrams for Step 1, 2 and 3

Figure D.3 shows the sankey diagram for step 3. Annual PV production sold to the external grid in step 3 is 3.6 % while 0.32 % of total energy input is stored in batteries.

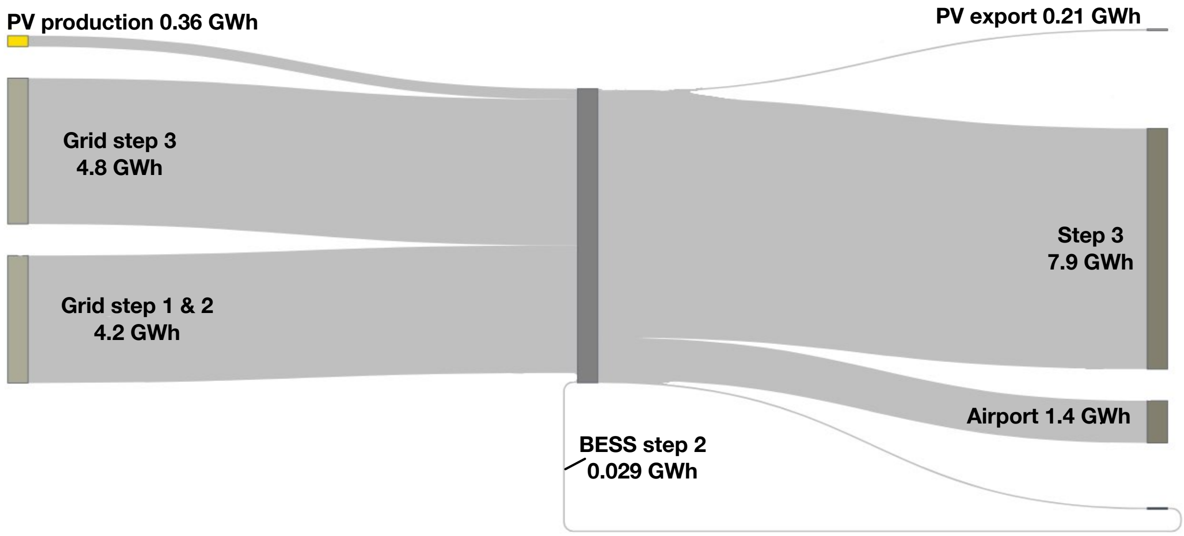


**Figure D.3:** Annual sankey diagram from PSS-DE®Siemens showing step 3. Edited from original.[80]

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