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Prepare for takeoff

Assessing the impact of electricity price variations on electric aviation potential at Visby airport

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Civilingenjörsprogrammet i system i teknik och samhälle

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Abstract

The electrification of the transport sector is an ongoing process that is aimed to reduce the global emissions of greenhouse gases. Electric aviation is one branch that is emerging by implementation of battery electric aircrafts. Due to weight issues, electric aircrafts are smaller than traditional aircrafts which leads to an opportunity for more regional aviation. One area where this is especially interesting is the island of Gotland.

Electric aircrafts also experience challenges at the airport. The aircrafts require high power to keep the charging time minimal which leads to a large strain on the grid. Therefore, it is interesting to examine how the energy system at Visby airport can be designed regarding production and storage and how different charging strategies can be implemented. Another important aspect is the cost of charging as the electricity price becomes central for electric aircrafts competitiveness.

To examine how the electricity price in the future, 2030, affects the cost of operation at Visby airport with different setups for the energy system, a Simulink model of the grid was created alongside a linear prediction model for the future electricity price.

The results show that a charging strategy with overnight charging gives the lowest net energy use from the overhead grid at 3,72 MWh per day. The electricity price in 2030 was predicted based on three estimation years with different characters: 2017, 2022 and 2024. The cost for the 24-hour operation is heavily dependent on charging strategy and estimation year which makes the total cost to vary from 3840 EURO at max down to 71 EURO as min. The fuel price per passenger is also dependent on charging strategy and estimation year and the results are ranging from 2,64 down to 0,57 EURO. Comparing with jet fuel, the price per passenger is 1,36 EURO.

To conclude, the choice of charging strategy has a big impact on the strain on the grid and the total cost of operation. The future electricity price will also play a part in what choice of energy system at Visby airport that is suitable. Lastly, regarding ticket prices, electric aviation can be competitive depending on charging strategy and price development in the future within this context.

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Populärvetenskaplig sammanfattning

Elektrifieringen är en ständigt pågående process i samhället där fossila bränslen fasas ut för att minska klimatförändringar och därmed den globala uppvärmningen. Flyget står för 2,5% av de globala utsläppen av växthusgaser genom förbränningen av framförallt jetbränsle. Inrikesflyget i Sverige är en sektor som siktar på att vara helt fossilfri till 2030 och därmed behövs andra lösningar än traditionella förbränningsmotorer till flygplanen. En lösning kan då vara att använda batterielektriska flygplan som drivs av förnybart producerad el. Dessa flygplan håller på att utvecklas och det finns till och med ett certifierat tvåsitsflygplan på marknaden.

De elektriska flygplanen har lite annan karaktär än de traditionella flygplanen i fråga om hur de fungerar. För det första är batterier betydligt tyngre per energiinnehåll, så kallad energidensitet, jämfört med jetbränsle. Detta skapar utmaningar med att flygplanen väger för mycket och därmed är de första elektriska flygplanen på marknaden mycket små. De flygplan som är på gång har cirka 30 sittplatser, detta kan jämföras med ett vanligt mindre kommersiellt jetplan som har omkring 250 sittplatser. Den mindre storleken är inte en nackdel utan en möjlighet för en ny bransch av inrikesflyget där mindre elektriska flygplan kan börja användas som regional transport och agera som bussar och tåg.

För att kunna använda sig av elektriska flygplan krävs det el, och mycket av det. Även de mindre flygplanen som är under utveckling har batterier i storleksordningen 1 MWh. Denna energimängd kan jämföras med omkring tio större elbilar vilket visar på hur mycket el som faktiskt behövs för att driva ett elektriskt flygplan. För att ladda flygplanen krävs det därmed en stor elektrisk effekt för att hålla laddningstiden låg och därmed konkurrenskraftig. Detta innebär en stor förändring i hur den elektriska infrastrukturen på flygplatserna behöver se ut. En mellanstor svensk flygplats som Visby flygplats använder i nuläget cirka 1 MW som mest. När elektriska flygplan ska laddas krävs det ungefär 1 MW per flygplan vilket gör att flygplatsernas elbehov, och därmed behovet av att producera mer el, ökar markant.

Genom att bygga upp en modell för elnätet på Visby flygplats kan flödet av el studeras och ge insikt i när man behöver köpa in el från det överliggande elnätet och hur behovet varierar beroende på om man har egen produktion och lagring av el på flygplatsen. För att undersöka detta användes fyra olika scenarion över hur energisystemet på flygplatsen kan tänkas se ut. Det som skiljde scenariona åt var hur flygplanen laddades och hur ett batterilager användes tillsammans med solceller för att minska behovet av elnätet.

Elpriser är också något som blivit mycket relevant och omtalat de senaste åren då Sverige har upplevt höga toppar och djupa dalar kring elpriset, framförallt år 2022. Hur elpriset kommer se ut i framtiden är något som är centralt för elektriska flygplans konkurrenskraft. För att undersöka vad elpriset kan tänkas vara år 2030 har en linjär prediktionsmodell tagits fram för att hitta relationen mellan behovet av el och det

slutgiltiga priset. Modellen har tränats på historiska data över elpriser och elbehov och tre olika scenarion för elprisets utveckling har tagits fram. Dessa tre scenarion kommer från träning av modellen på tre olika år: 2022, 2017 och 2024. Dessa tre år användes på grund av elprisets unika karaktär de åren. 2022 var ett kaosartat år som genererade höga medelpriser och en hög volatilitet, det vill säga variationen i priset från timme till timme. 2017 var ett stabilt år med lågt medelpris och låg volatilitet medan 2024 kan beskrivas som korsningen mellan de två med ett lågt medelpris men hög volatilitet. Genom att träna modellen på dessa tre år och sedan utvärdera på behovet av el som Sverige och framförallt industrin kommer ha år 2030, kunde tre olika prisscenarion erhållas.

Genom att kombinera prisscenarion med elnätsmodellen erhölls kostnader för rena elpriser att ha elektriska flygplan på Visby flygplats. Denna data användes i sin tur för att räkna ut ett bränslepris per passagerare som kunde jämföras med de vanliga flygplan som används idag. Resultatet visar att det finns konkurrenskraftiga alternativ där bränslekostnaden per passagerare är betydligt lägre jämfört med vanliga flygplan men det hela hänger på vilken utveckling elpriset har. Resultaten visar också en känslighetsanalys som innebär att storleken på en viss parameter varieras för att undersöka hur den påverkar slutresultaten. Storleken på ett batterilager är något som har undersökts i denna studie som visar att mycket finns att vinna på att ha ett större batterilager då man både kan spara pengar och minska belastningen på elnätet vid höglasttimmar.

Det finns även flera aspekter som påverkar vad biljettpriserna blir i framtiden utöver kostnaden för enbart bränslet. På grund av utmaningar med vikt för flygplanen krävs andra materialval som är mer lättviktiga för själva konstruktionen som innebär en ökad kostnad. Det finns också utmaningar för de elektriska flygplanen i form av laddning då batterier som laddas med hög effekt kräver kylning samt att det påverkar deras livstid. Därmed finns det många aspekter som kan påverka de elektriska flygplanens konkurrenskraft där forskningen behöver komma längre.

Slutligen ska det påpekas som tidigare nämnt att den största drivfaktorn för elektrifiering är att minska utsläppen av växthusgaser och därmed minska klimatförändringar och global uppvärmning. Genom att elektrifiera flygplanen på Visby flygplats kan besparingar ske i utsläppsväg men det ska tilläggas att Visby är en mindre flygplats och bara en. Om liknande elektrifiering sker på fler flygplatser är man på god väg att lyckas med målet om fossilfritt inrikesflyg 2030.

Acknowledgements

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Thomas Norström, Uppsala May 2025

Table of contents

1. Introduction

Electrification is an ongoing process in many disciplines all over the world with the main goal of reducing global emissions of greenhouse gases and reduce the impact on the climate. One sector where the electrification is a very present process, is the transport sector. Cars are being electrified at a rapid pace and combustion cars are being phased out and even prohibited in certain areas [1]. The transport sector as a whole is emitting around 20% of the global emissions [2] and in Sweden, the share is 31% [3]. The main contributors to the emissions are the cars and the trucks. But there is one other key area that contributes largely to the emissions which has not come as far along in the electrification process, namely aviation. The aviation stands for 2,5% of the global emissions [4] and is aiming to reduce this negative environmental impact.

The main part of the emissions from the traditional internal combustion engine (ICE) aircrafts is combustion of the fossil fuel which is used in jet engines. Fossil fuels are in the beginning of being phased out and replaced with sustainable air fuel (SAF). This fuel is a biofuel, often originating from residual products from forestry or commercial kitchens but it can also be produced synthetically [5]. The downside is that it is very expensive compared to regular fossil fuel and therefore not as competitive [6]. One fuel type that is very financially competitive is electricity. Electrical aircrafts (EA) are starting to enter the industry with a small aircraft that is already certified, the Velis Electro [7], and other manufacturers with models coming in the near future. One upcoming project that is being developed is the Swedish manufacturer Heart Aerospace and their ES30 model. This aircraft is an electric hybrid which has the capacity to carry 30 passengers [8]. The biggest challenges for the EAs are the weight and the range. The batteries are heavier and have a lower energy density compared to jet fuel, around 200-500 Wh/kg compared to 12000 Wh/kg [9], [10]. The batteries energy density is expected to increase in the future to numbers upwards of 1000 Wh/kg or even further depending on the material in the battery, but it is still not close to the energy density of jet fuel [10], [11]. This is one explanation of the limited size seen in early electrical aircrafts such as the ES30, whose capacity for 30 passengers can be put in comparison to that of common ICE aircrafts like Airbus A320 which can carry around 250 passengers [12].

The small size of the EAs, however, is not only a negative aspect but an opportunity to transform the regional aviation. In Sweden, the domestic flight has the goal to be fossil free in 2030 [13] and these flights are often not in need of a large jet plane and therefore smaller EAs become quite interesting. One place where this opportunity is especially interesting than in other places is the island of Gotland which is located four hours east of the mainland or approximately 200 km from Stockholm. Four hours is the distance with a ferry from either Nynäshamn or Oskarshamn. However, in Visby, a regional airport is located where one can fly to the mainland which only takes around 40 minutes [14]. The island is heavily dependent on well functioning transports to get closer to the mainland and therefore EAs are being examined [15], [16]. The possibilities and desired

outcomes with EAs are to get cheaper and more environmentally friendly transports compared to the traditional ICE flights, a faster transport compared to the ferry and a possibility to connect to other cities with regional airports such as Kalmar, Norrköping and Linköping and not only be connected to Stockholm [17]. A typical range for an EA in the near future is around 200 km [18] and with that range, many medium sized Swedish cities are in reach. The EAs have another benefit compared to ICE aircrafts which is well known from the car sector, namely, the sound and noise. As the EAs are smaller, quieter and less vibrant, the impact on the world heritage town of Visby is lessened. This is an advantage of the EA as it means that the plane can travel closer to city centres and become more of a regional transport such as trains and buses and not only long-distance international travel.

Even though the aircrafts are capable of flying with electricity as a fuel, there are other challenges that occur on the ground, at the airport. To maximize the revenue of an aircraft, it is key to keep the turnaround time, i.e. the time on the ground between landing and another take-off, to a minimum [19]. To fuel an ICE aircraft is quite easy and time efficient but this is not the case for an EA. To charge a large battery is time consuming and technically demanding. To keep the charging time at a minimum, large powers are needed which demands more of the electrical grid and the energy system, especially in a time of a nationwide power deficit [18], [20]. In the recent years, the volatility of the electricity price has also been a central aspect. This might lead to ticket cost that varies quite largely with the price of the fuel which could be a negative impact on the airline and the customers.

The charging of the battery is also a whole scientific field of its own. There exist many ways to charge an EA and they all have different advantages and disadvantages. Firstly, the location of the charger is a difficult question. Should one have many chargers located at each gate or fewer chargers at only selected locations at the airport? Many gates with chargers are time efficient as many aircrafts can charge simultaneously but highly expensive as the infrastructure is costly. To have fewer chargers is not optimal for simultaneous charging but most of the time, the aircraft will not charge, and therefore it could be more cost effective to have fewer chargers that have a higher utilization. One could also have a mobile charging unit that comes to the plane. This option could be more suited to smaller regional airports such as Visby as there are no gates with landing bridges but only a parking space outside of the terminal [18].

Then the power comes into account. Lower power means longer charging time but more gentle to the battery which leads to a lower degradation and a longer lifetime which could be more financially viable [21]. All of this must be considered when the EAs are starting to appear at the airports.

1.1 Aim

The aim of the study is to investigate how the variation of the price of electricity impacts the energy system at an airport, including choices of production, storage and

strategies for charging of electrical aircrafts. The evaluation of different strategies and scenarios will be done from an economic and technical perspective and applied to the case of Visby airport at the island of Gotland. The goal is to understand how variations in the price influence the competitiveness of electric aviation compared to traditional ICE aircrafts and what impact electric aviation can have on the island of Gotland´s regional development and transport situation.

1.2 Research questions

To reach its aim, this project explores the following research questions:

- Which are suitable strategies for charging electric airplanes to keep the cost of electricity at a minimum?
- How will the development of the electricity price impact the choice of energy system at Visby airport?
- How does electric aircrafts compare to ICE aircrafts regarding ticket price and environmental impact?

1.3 Methodology

The methodology used in this project consists of two models. One for simulating the energy system at the airport to investigate the power flow with the aircrafts being represented as electrical loads. Another model was used to estimate the electricity prices in the future given different scenarios of how the energy system will look in the future based on past prices. This predicted price was then implemented in the simulation model to investigate what combinations and setups of the energy system that would be most cost effective. Lastly, the cost of different energy systems setups was transferred to and narrowed down to ticket prices for flying electrical and then compared to traditional ICE aircrafts. The methodology is explained in detail in section 3.

1.4 Limitations

The study is limited to exploring Visby airport and thereby limited to what factors that will be suitable for that specific location such as electrical parameters. Also, the Heart Aerospace ES30 is the electric aircraft that the simulation parameters are based on. Other electric aircraft concepts exist but remain outside the scope of this project.

2. Background

2.1 Electricity situation on Gotland

Gotland is a part of the electricity price area SE3 which is the same area as Stockholm, Uppsala and many other large Swedish cities. However, the electricity situation on

Gotland is not the same as in the rest of SE3 as the island is not synchronously connected to the mainland. Its current connection consists of two HVDC subsea cables with 130 MW capacity each that are soon to be retired [22]. Soon, in 2031, Svenska Kraftnät is planning to add two more subsea cables with 220 MW each. This time in form of 220 kV AC which makes Gotland synchronous with the mainland [23]. Gotland has some electricity production of their own with a large share of wind- and solar power as well as some incineration [24]. The island consumes a small part of the entirety of SE3, but the demand is expected to increase, hence the addition of new cables. Gotland as a whole consumes around 850 GWh per year and produces around 460 GWh per year [25], [26]. The city of Visby where the airport is located can be assumed to stand for a large share of the consumption as it is the biggest city. The airport itself uses around 1 MW, but the capacity is being increased to 10 MW. The usage over a year results in a consumption of 2,6 GWh each year [27]. If one assumes that the electricity consumption is linearly related to the population on Gotland, it will lead to Visby standing for 55% of the consumption, i.e. 473 GWh. This makes the airport having a share of the consumption of 0,5% [28].

By implementing EAs in a large scale, the need of electricity will only go up. Some studies made at the airport shows an increase in consumption of nearly 100 percent [17]. This creates a challenging situation as there might be other places and sectors that require that electricity. This means that the region must decide on what is most important, electrification of the aircrafts or other sectors such as industrial manufacturing. SE3 is also in a strained situation with a power deficit and a lot of areas that desire to electrify themselves [20]. Despite the two planned cables, there are still uncertainties on the reliability of a secure power supply. Therefore, it is also of interest to examine the possibility of more production at the airport itself. As the aircrafts require a lot of power to charge and it is desirable to be able to charge at any given moment, it might be wise to have an own energy system with production and storage at the airport for redundancy if the grid is not able to always deliver.

This airport grid would consist of both production and storage to increase the charging capacity. Many energy sources and storage types could be useful and functional at the airport. Solar power (PV), wind turbines, batteries (BESS), hydrogen or flywheels are all technologies that may be suitable for an airport. Solar power is widely used at a Dutch airport in Groningen with a 22 MW solar park installed between the runways which shows the potential of the technology [29]. There are, however, a lot of difficulties with installing electrical facilities at an airport. If you are inside of 6 km from the air traffic control tower, CNS analysis must be performed to investigate the potential impact on communication, navigation and surveillance according to Swedavia. If the wind turbine is high enough, i.e. over 20 m, it must undergo an aviation obstacle analysis [30]. Solar panels might also lead to problems with glare for pilots which makes the placement of the panels a key area.

2.2 Visby airport and electric aviation

Visby airport today, is a medium sized Swedish airport owned by Swedavia, that only have regular connections to Stockholm Arlanda all year round. The airport is open from around 06.00 to 24.00 and has approximately 10-14 take-offs and landings on a workday and 16 on the weekend [31]. This leads to yearly flight statistics of 3200 domestic flights, 5000 flights in total and around 318 000 passengers at Visby airport [27], [32]. There is also a military presence at the airport in form of F17 which significantly increases the sensitivity in the aspect of what you can do energy wise at the airport and how reliable and resilient the systems must be [27].

The only EA that is certified for use is the Velis Electro [7], but the certification is not yet fully completed. EASA has not made its stance clear about the risk of fire onboard an EA. Before this is done, no EA will be fully certified for use as it is too risky to construct the aircraft and then hope to get certified which is the case right now. EASA states that anyone is welcome to try to get certified, but they have no guidelines regarding the fire safety at the moment [33]. The same problems exist on the ground regarding batteries as energy storage. The risk with batteries is a thermal runaway that is very difficult to extinguish [34]. This means that the airport might have to change their routines regarding charging and therefore to slow-charge overnight without personnel present might be deemed too risky.

2.3 Price of electricity

The price of electricity and the variation of the price are of utmost importance for the success of electric aviation. SE3 has in the recent years experienced higher and more volatile prices as the energy situation in Europe has been exposed to disturbances due to Russia´s invasion of Ukraine in 2022. SE3 has also lost multiple nuclear reactors [35], making the zone more dependent on transmission from the northern parts of Sweden and other countries. The Swedish energy system has also been transformed into more and more intermittent power sources such as wind and solar. How the future prices will be is difficult to forecast. This is because of the large transformation that is ongoing in the Swedish energy system with the possibility of multiple new nuclear reactors and multiple expansions of the transmission grid [36]. A large share of intermittent energy can often lead to large fluctuations in the electricity price with changes in the weather [37], [38] but it is not certain that a large share of base power will lead to lower, more stable prices [39]. The variations in the price which from March 18th 2025 will be set on a 15 minute basis [40] makes charging strategies a key area to keep cost at a minimum. The variation in the price over 24 hours can be very large and variate in ranges from 0 SEK/kWh to 1,5 SEK/kWh on a normal day [41]. On an unnormal day, the fluctuations can vary greatly. If you have multiple aircrafts charging their batteries that have a large capacity, in the MWh range, the price for one charge can differ with thousands of SEK. The price will also impact charging strategies further as a new power tariff is being implemented at the speaking moment [42]. This means that a charging strategy with a

high power will be more costly as it is a bigger strain on the grid. Due to all these factors, the price of electricity is a key area in electric aviation.

3. Methodology

3.1 Overview of methodology

The methodology used in this project is explained in more detail below. In Figure 1, an overview of the methodology and how the different parts relate to each other can be seen.

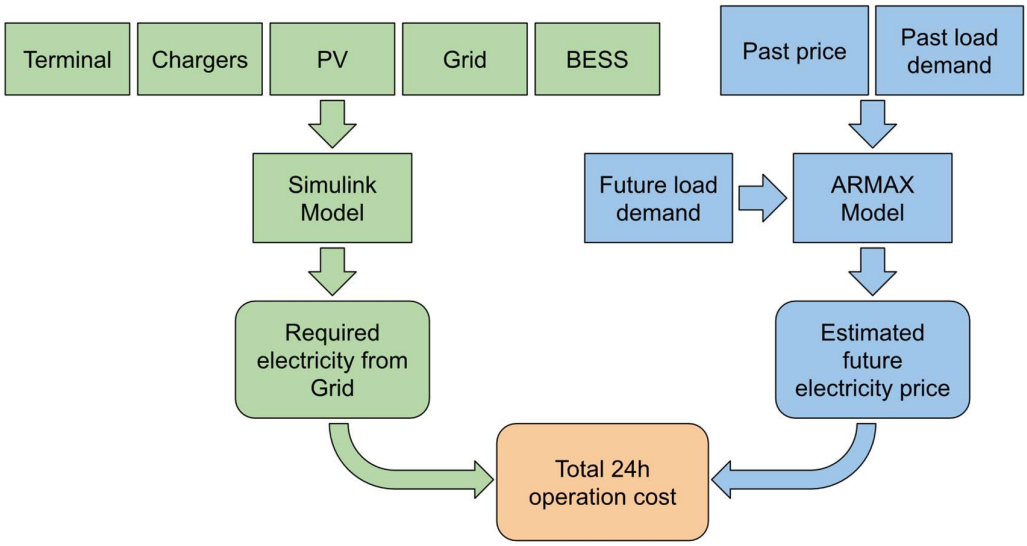

Figure 1. Overview of the methodology used in the project. PV = photovoltaic electricity, BESS = Battery energy storage system.

3.2 Electrical grid at Visby airport

The electrical grid at Visby airport has been modelled in Simulink as blocks using the Simscape Electrical package. Simulink is a graphical programming interface where one uses blocks to create physical models [43]. In this way, the energy system has been drawn up with all its components on an overall level. The model includes loads that symbolize the chargers for the aircrafts. The loads are equipped with a shape that is multiplied with the charging power to illustrate the difference in utilization depending on time of day. The model includes four chargers and a terminal that all are related to a shape to illustrate the loads variation during the 24-hour simulation.

The grid was setup for a power flow analysis which means that the focus lies on the power flow in the system and not so much on the voltage and current across and through each component. As the grid was developed on an overall level, only active power was considered with the reactive power production and consumption being ignored. The generators in the system are illustrated by a load flow source in the model and thereby not specified as one type of production such as solar or incineration. One generator is implemented as a swing bus that acts as a reference for the voltage and phase angle. This swing bus symbolizes the overhead grid operated by Gotland Energy (GEAB) that the airport is connected to that supplies the airport with power today. The swing bus, i.e. the grid, only delivers the amount of power that is needed to fulfil the demand from the loads that the other generators cannot satisfy. These two other generators are a photovoltaic (PV) installation and a battery energy storage system (BESS). The PV is equipped with a shape that results to a higher yield at 12 o´clock compared to the evening. However, due to numerical simulation reasons, this shape was simplified to a shorter window with full power from a longer window with gradually increasing and decreasing power output. The BESS was also simplified to a generator that can both produce and consume power to keep the model as simple as possible. The BESS was charged in two ways, during the night at a lower power level when the electricity is typically cheaper and the demand of electricity is lower from other parts of the local region, or, only from the PV production to maximize self-consumption of electricity. The BESS was then used during the day to help lower the need to purchase extra power from the grid. All the loads, production and transmission were connected to each other using buses. An overview of the modelled grid can be viewed in Figure 2 and data about the components can be found in Table 1.

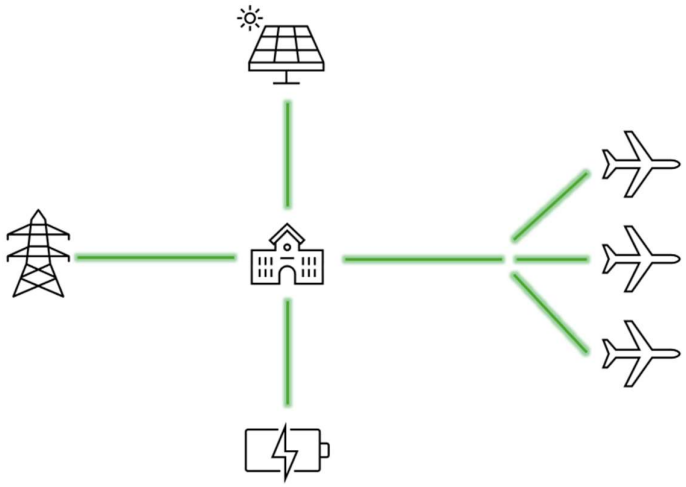

Figure 2. Overview of the airport energy system. Consists of the GEAB-grid, BESS, PV production, terminal building and EA chargers.

Table 1. Details about the airport grid.

Component	Value	Comment
Base voltage	11 kV	Assumption
Solar power	1 MW	[44]
Terminal power	200 kW	Assumption
Battery power	550 kW	Assumption
Battery capacity	2,2 MWh	[17]
Battery charging power	200 kW	Assumption
EA capacity	1 MWh	[18]
Number of chargers	4	Assumption
Number of flights per day	10	Assumption

The simulation of the power flow was then executed with two different types of scenarios for charging of the aircrafts and for charging the BESS. The first scenario was the daytime scenario with charging of the BESS during the night. This was built up with a combination of the current flight schedule [31] and a recalculation of the passenger capacity from ICE aircrafts [45] to an EA [8]. The developed schedule was then implemented with high power charging during one hour before every departure which can be seen in Figure 3. The simulation then results in power flow curves during the 24-hour simulation. The simulation was executed by using the inbuilt solver function in Simulink to solve the differential equations that the Simscape blocks illustrates. The second daytime scenario was constructed in the same way but now, only using PV electricity to charge the BESS which leads to a higher self-consumption of PV electricity. The result is again a power flow curve from the grid that are directly related to how the PV produces and the BESS is being charged and discharged. Data with information about the specifics of the daytime scenario can be found in Table 2.

Table 2. Specifics about the daytime scenario.

Component	Value	Comment
Charging power High	1 MW	[18]
Charging power Low	300 kW	Assumption

The second type of scenario is a night scenario. This scenario implements the same developed flight schedule but with the two aircrafts that are staying overnight being

slow-charged during the night with a lower power, see Figure 3. This also leads to a change in how the BESS is implemented to help reduce the need of the grid. The remainder of the flights are then charged with high power similar to the first scenario. This scenario also has a variation in how the BESS is being charged. Firstly, during the night alongside the aircrafts and secondly, only during the day with PV. Both the nighttime and daytime scenarios also include one charger being used to charge smaller EAs such as the Velis Electro and other non- commercial flights with a lower charging power. Specifics about the nighttime scenario can be seen in Table 3.

Table 3. Specifics about the nighttime scenario.

Component	Value	Comment
Charging power High	1 MW	[18]
Number of EA´s overnight	2	Assumption
Charging power Low	200 kW	Assumption

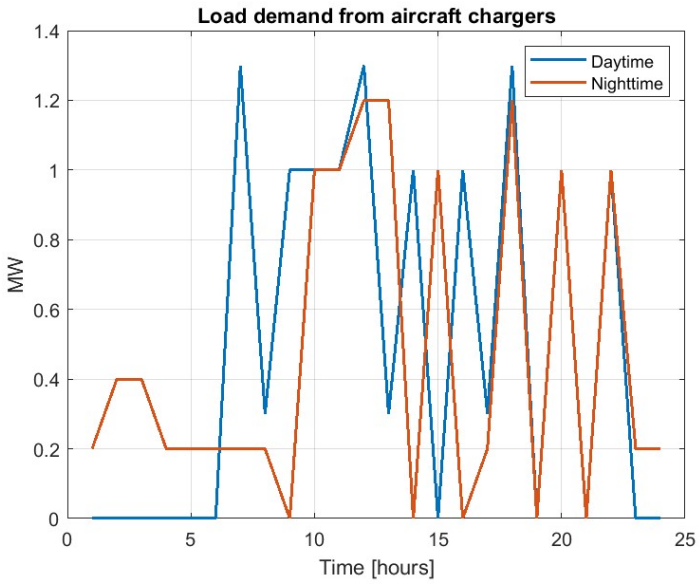

Figure 3. Load demand from the aircraft chargers during 24 hours for the two different scenarios.

3.3 Prediction of electricity prices

The second part of the modelling was the prediction of electricity prices in the future. This has been done by looking at past prices from the start of 2015 to the end of 2024 and predicting them onto the year 2030 as this is the year when the domestic flight in Sweden is going to be fossil free [13]. The prediction has been made using the System

Identification Toolbox in Matlab and the Ident App [46]. By plugging in input and output and then estimating a linear model, one can achieve a prediction model based on past data in SE3 and use it to forecast future data. The model used in this case was the ARMAX model with 24 parameters meaning that the past 24 hours are being used to predict the future price. ARMAX stands for autoregressive moving average with exogenous input and is a common model used in timeseries analysis [47]. The input, u(t), is the load demand and the output, y(t), is the price of electricity. The model also include noise, e(t), that is disturbances and variation in the data. Before estimating the model, the data was prepared by removing leap years and replacing incomplete data, NaN, with the mean of the dataset. The ARMAX model with 24 parameters has the form shown in equation 1.

$$y(t) = -a_1 y(t-1) - \cdots - a_{24} y(t-24) + b_1 u(t-1) + \cdots + b_{24} u(t-24) + c_1 e(t-1) + \cdots c_{24} e(t-24) \quad (1)$$

The number of parameters was set at 24 due to when evaluating and comparing different model orders, this order was the one that represented the data in the best fitted way. A higher model order was also possible, but this mostly leads to larger calculations and therefore longer simulation times without any substantial improvements. Using lower orders does not capture the characteristics of the electricity prices and generates more of a copy of the input. It should be noted that it is a major simplification to only have the load demand as input. In reality, there are multiple factors that come together to set the price such as transfer capacity, type of energy and the demand in other electricity areas [48]. To compensate for this simplification, a large data set was used to find the parameters that describes the relation between the load demand and the price. The 24 parameters are chosen by iteration and evaluating on goodness of fit by the Ident App.

In this case, the ARMAX model has been used in a different way compared to what is usually done in System Identification. Normally, one divides the data set into estimation data and validation data and uses the model to examine the system. By using 24 parameters, this usually leads to overfitting on the estimation data and then a lower goodness of fit for the validation data. In this case however, an entire year's worth of data was used as estimation data and no real validation data existed as the model is then used to simulate the 2030 scenario using estimated load demand for 2030. By doing this, the results give more of an example of how the price might become depending on what estimation data is used and not how well it behaves compared to the real data of the estimation year [49].

Three different years were used to predict the price in 2030. These include the chaotic year 2022, the average year 2024 and the low and stable year 2017. These years were chosen given their characteristic by evaluating on mean price, standard deviation and interquartile range. How the characteristic of each year compares to one another can be viewed in Figure 6. By fitting an ARMAX model to these years and evaluating on the year 2030, three different price scenarios were obtained. The input in 2030 was estimated based on forecast on how the demand will increase in SE3 to 2030 compared

to nowadays [50], [51]. As the prediction is simplified and a lot of uncertainties exist regarding the energy system in the future [36], noise was manually added to better represent the price in the future. The noise was based on the prediction model´s uncertainty and residuals, and random events that might lead to peaks and disturbances in the price.

After obtaining different prices scenarios for 2030, these were combined with the different charging scenarios to estimate what the price of charging the EAs will be. Due to that the electricity price often can have seasonal variations, the evaluation was done in all four quarters of the year to achieve more broad results.

Lastly, a comparison between jet fuel and electricity as aircraft fuel was made. This was done to achieve a comparison between the price of fuel per passenger to be able to obtain an insight to what ticket prices in the future might cost. The price per passenger was calculated by adding the cost of electricity for each charge and dividing them by the number of passengers per aircraft. The cost evaluation was only performed on the month of July and not examined for January, April and October as the other results has been. This was because July is the, by far, busiest month for travel [32] and therefore the most interesting time to evaluate on. This number was then compared to the same price per passenger for traditional ICE aircrafts driven by the fuel JetA1. Lastly, an environmental comparison was also made to examine what kind of CO_2 emission savings are possible. This was done by looking at statistics of fuel consumption at the airport and the CO_2 containment per litre of fuel.

3.4 Sensitivity analysis

To find out how the size of certain components affects the final values, a sensitivity analysis has been carried out. The sensitivity analysis was done on the size of the BESS as it is a component that is highly expensive and therefore very interesting to study its impact on the results more thoroughly. The simulation was repeated three times with three different sizes of the BESS, all based on one scenario. Here, the original size of the BESS as mentioned above in Table 1, was doubled, halved and lastly, set to zero. This allowed for a more thorough examination of the impact of the size of the BESS and how much it affects the grid and the energy system at the airport. The altering size of the BESS was modelled as half the original capacity but with the same power and in the doubled case, twice the capacity but still the same power. The output power of the BESS was not altered due to simulation reasons. Other parts of the grid such as PV capacity or number of flights were not examined in the sensitivity analysis because they were deemed too uncertain or not relevant. The number of flights in the future are not certain and mainly up for speculation. Therefore, they were not examined in the sensitivity analysis. Regarding the PV, this technology has existed for a while and is already quite cost effective and developed and therefore not a component that might impact the system greatly.

4. Data

To estimate the electricity price in 2030, past prices were used with past load demand as input. The data is hourly from 2015 to 2024 with the three leap years being modified. Below, one can see the load demand and electricity prices from 2015 to 2024 in Figure 4 and Figure 5.

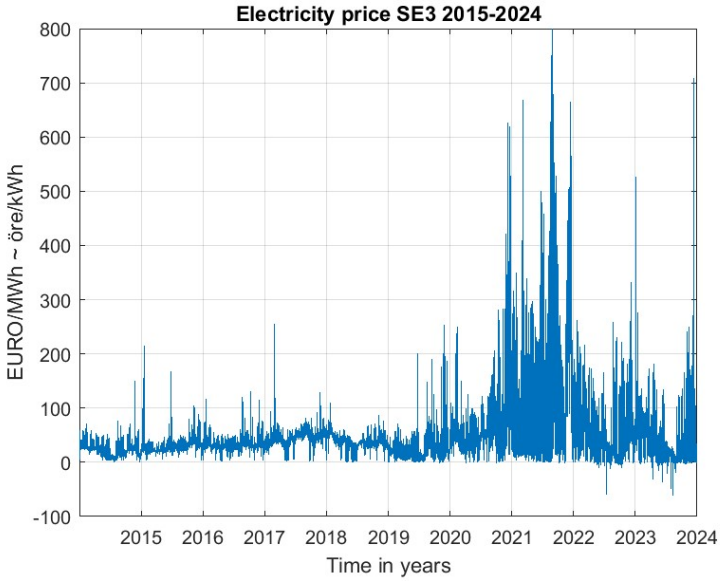

Figure 4. Electricity prices in SE3 from 2015 to 2024 in EURO/MWh [52].

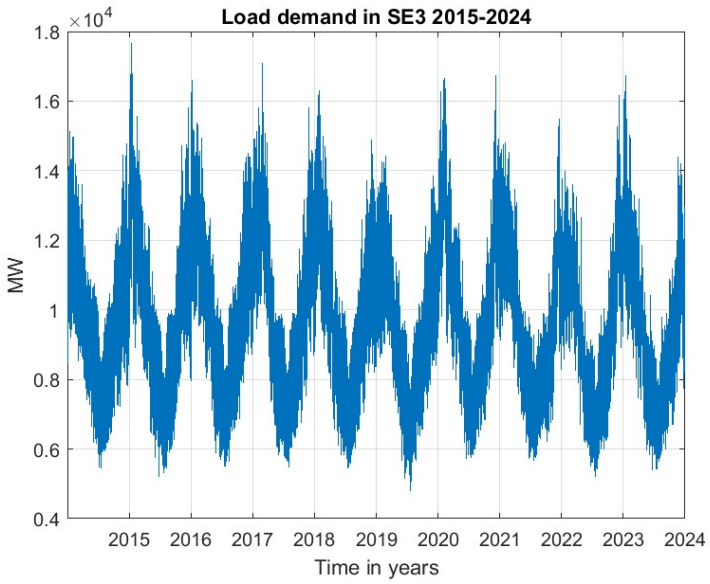

Figure 5. Load demand in SE3 from 2015 to 2024 in MW [53].

To find out how the years compare against each other, mean values, standard deviation and interquartile range were obtained which can be seen in Figure 6.

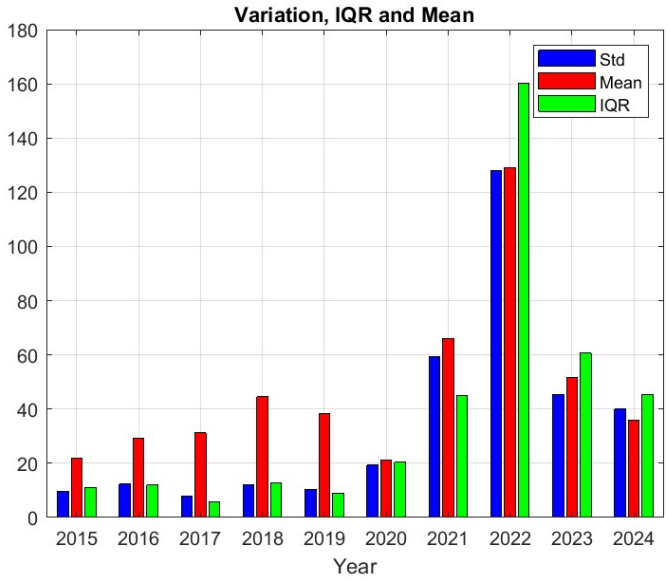

Figure 6. Barplot of the mean values, standard deviation and interquartile range of the electricity prices from 2015 to 2024.

5. Results

Below the results are presented. Firstly, results from the power flow analysis done in Simulink. Secondly, results from the prediction of electricity prices from the different scenarios and thirdly, the parts combined resulting in a total cost for a 24-hour simulation presented for four different days per year to catch seasonal variations. Fourthly, everything considered together to result in a comparison of ticket prices between EAs and traditional ICE aircrafts as well as environmental aspects. Lastly, the results from the sensitivity analysis on the capacity of the BESS is presented with power flow and the total cost for the 24-hour operation.

5.1 Simulation of the airport power grid

The first scenario that was evaluated was the nighttime scenario with nighttime BESS charging. This scenario leads to a limitation of the number of power peaks with two of the flights being charged slowly during the night alongside with charging of the BESS at a low power level. During the day, overproduction from the PV becomes notable and therefore the airport grid delivers power to the GEAB grid resulting in a net energy use of 4,43 MWh.

The second scenario was again nighttime charging of the aircrafts but now with PV charging of the BESS. This leads again to a limitation of the number of power peaks but also a higher self-consumption of the PV produced power. By charging only with PV, the power peaks at night becomes a little lower. In this scenario, similarly to the first,

the overproduction from the PV is still notable resulting in a large delivery to the grid during the day. However, by raising the self-consumption level, the net energy drawn from the grid was significantly lowered to 3,72 MWh.

The second type of scenario that was evaluated was the daytime scenario. Firstly, with nighttime BESS charging. This scenario leads to more power peaks during the day but a lower power flow during the night. This scenario also presents an overproduction of PV power during the day but, as the self-consumption is lower due to charging the BESS with grid power, the net energy use from the grid is higher compared to the two previous scenarios at 4,75 MWh.

The last scenario for the power flow analysis is the daytime scenario with PV BESS charging. By charging the BESS with PV power leads to no power being drawn from the grid during the night. The power peaks are still there but the overproduction is lowered by increasing the self-consumption. This leads to a lower net energy use at 4,17 MWh.

All the above presented scenarios' power flows from GEAB can be seen together for an easier comparison in Figure 7.

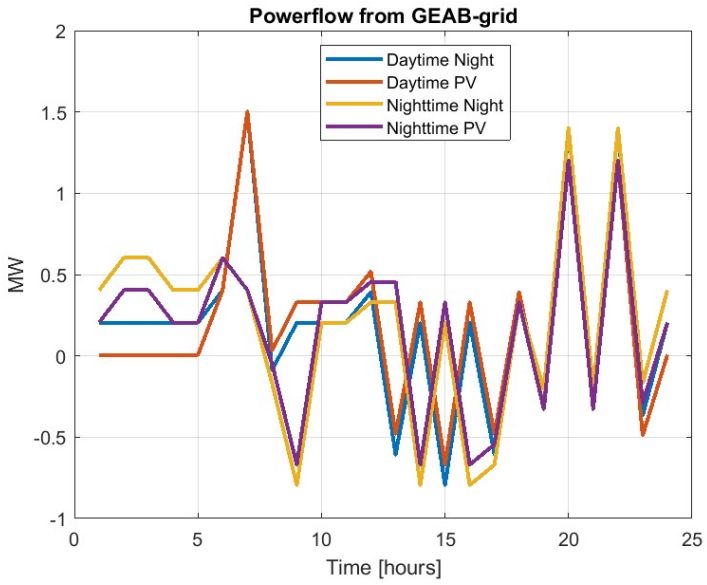

Figure 7. Power flow from GEAB- grid in all scenarios.

5.2 Prediction of electricity prices

Below, the estimated prices for 2030 are presented for the three different estimation years: 2022, 2017 and 2024. Firstly, in Figure 8, the estimated price based on the

chaotic year of 2022 is presented. This leads to a high mean with a high variety and high peaks in the price which occur frequently.

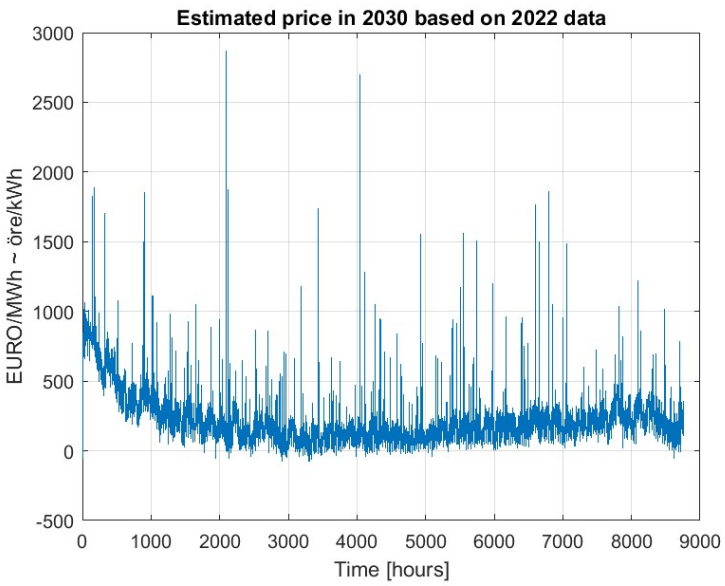

Figure 8. Estimated price in 2030 based on the estimation year 2022. Mean: 213 EURO/MWh, Maximum: 2865 EURO/MWh.

Secondly, in Figure 9, the estimated price based on the calm and stable year 2017 is presented. This estimate leads to a low mean with low maximum peaks as well. The peaks come quite seldom, and the price generally lies close to the mean.

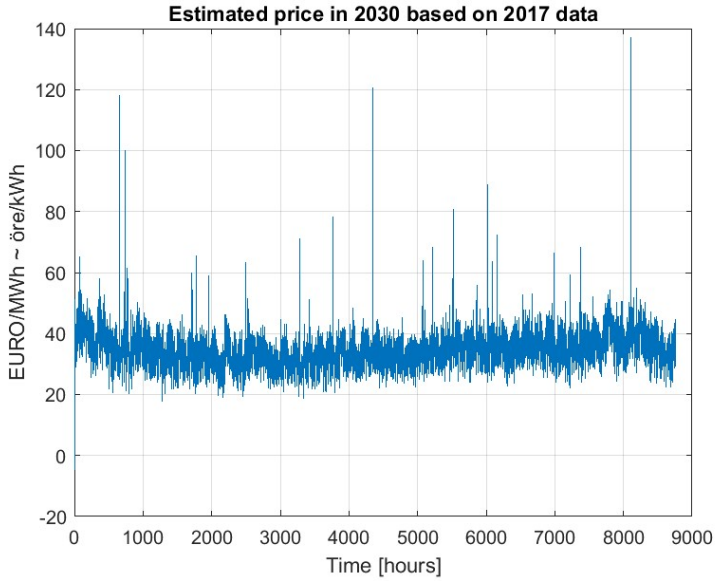

Figure 9. Estimated price in 2030 based on the estimation year 2017. Mean: 34 EURO/MWh, Maximum: 137 EURO/MWh.

Lastly, in Figure 10, the estimated price based on the quite average year of 2024 is presented. This estimate gives a quite low mean value, but the variation is more notable and generates high peak values compared to the 2017 estimate.

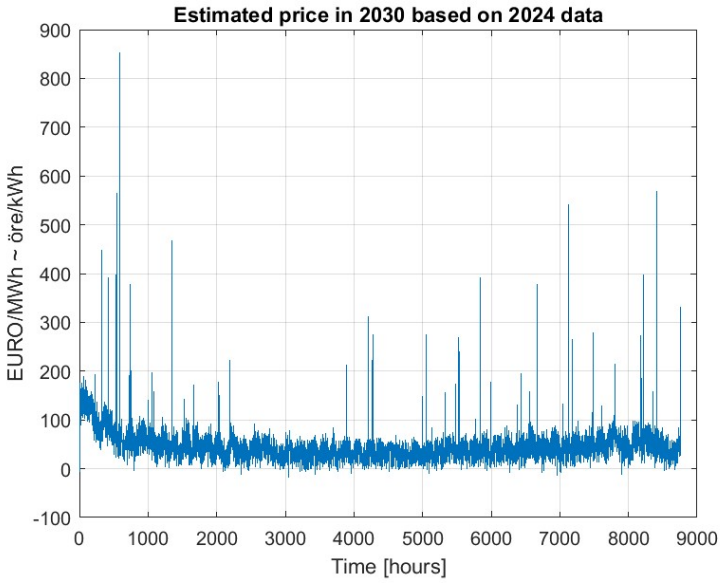

Figure 10. Estimated price in 2030 based on the estimation year 2024. Mean: 44 EURO/MWh, Maximum: 853 EURO/MWh.

5.3 Total cost for 24-hour operation

Below one can find the combination of the power flow with the prediction of future electricity prices. To get a broader result and get rid of the effect of seasonal variations, the cost was estimated on four different dates during the year at all different seasons. The result for the four different scenarios is presented in Figure 11 and Figure 12.

5.3.1 Nighttime scenarios

In Figure 11 below, the difference in cost between charging by night or only charging with PV can be seen. The figure shows that by charging with PV, the cost is mostly lower than if one charges in the night with the use of the grid. The difference is most substantial in the cases where the price is higher, such as January and October when using the 2022 estimation data. In the other cases, the cost is quite similar between the two different scenarios.

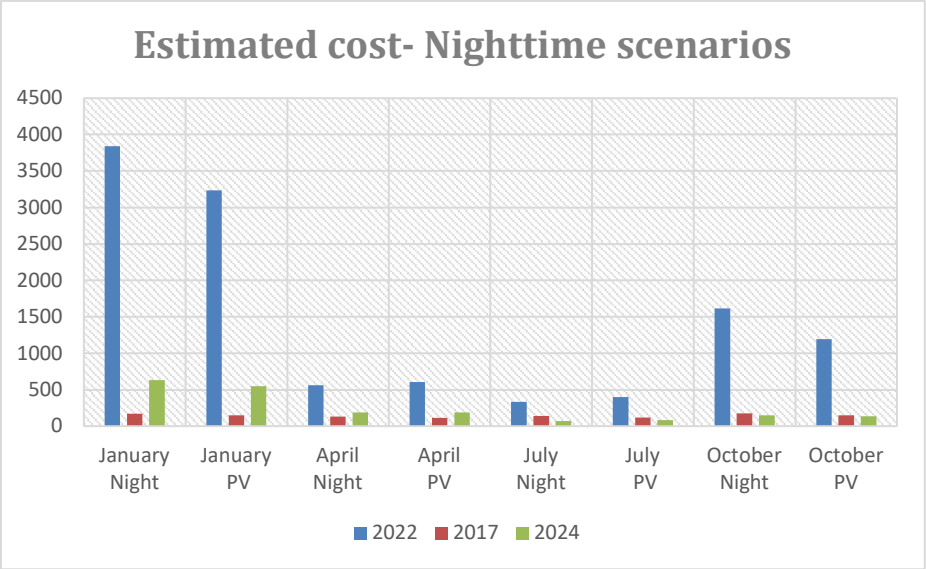

Figure 11. Estimated cost for 24-hour operation on the 2nd of January, April, July and October with the nighttime scenario with nighttime charging and PV charging.

5.3.2 Daytime scenarios

In Figure 12, one can see similar behaviour as in the nighttime scenario. The cost is generally lower in the PV charging case than in the charging by night case. Especially in the more costly months January and October. However, in April and July, the cost by using PV charging is marginally higher than charging by night.

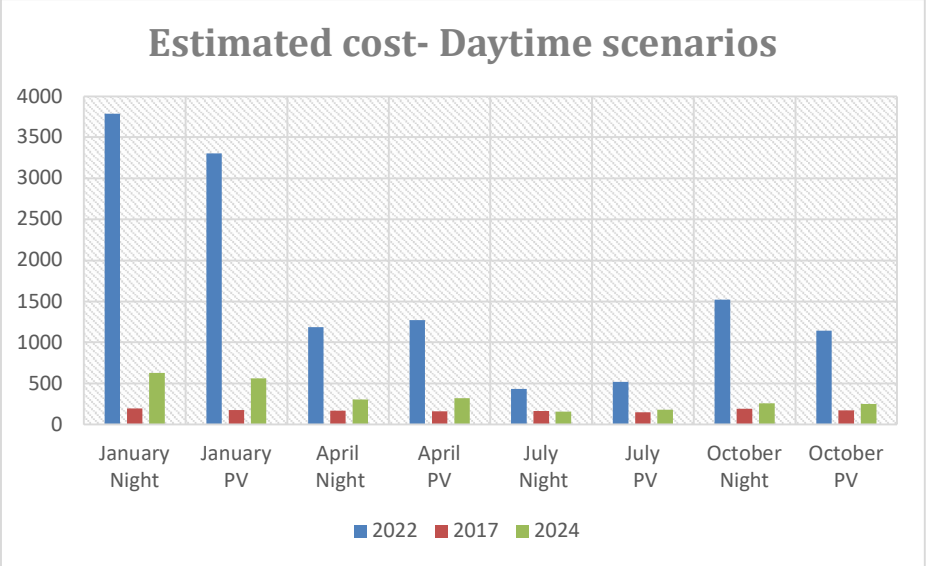

Figure 12. Estimated cost for 24-hour operation on the 2nd of January, April, July and October with the daytime scenario with nighttime charging and PV charging.

5.4 Ticket price- and environmental comparison

Below, in Table 4, the price of charge per passenger is presented. This is the price per passenger based on the average cost of the 10 flights that are being charged per 24 hours.

Table 4. Estimated ticket price based on electricity cost on the 2nd of July.

Estimated ticket price [EURO]	Scenario	BESS Charge	Training year
2,64	Daytime	PV	2022
0,6	Daytime	PV	2017
0,73	Daytime	PV	2024
2,45	Daytime	Night	2022
0,57	Daytime	Night	2017
0,66	Daytime	Night	2024
2,29	Nighttime	PV	2022
0,61	Nighttime	PV	2017
0,57	Nighttime	PV	2024
2,37	Nighttime	Night	2022
0,72	Nighttime	Night	2017
0,61	Nighttime	Night	2024

To compare the ticket prices in Table 4 with traditional ICE aircrafts and the price of the fuel JetA1, the following calculations, shown in equation 2, have been made based on values in Table 5.

Table 5. Details about fuel consumption.

Number of commercial landings	3300	[27]
Sold fuel at airport	500 m3	[27]
Price of fuel	6 SEK per litre	[54]

Ticket price	~1000 SEK	[55]
Seats per aircraft	60	[45]

$$3300\ landings\ per\ year\ \Rightarrow \frac{500m3}{3300} = 150\ litres\ per\ plane \Rightarrow 150 \times 6\ SEK\ per\ litre$$
$$\approx 900\ SEK\ per\ plane \Rightarrow \frac{900}{60} = 15\ SEK\ per\ passenger\ \approx 1{,}36\ EURO \quad (2)$$

The ticket price now, however, is around 1000 SEK one way which means that many other additional costs are also present. However, the comparison provides insight into what ticket prices EAs might generate in the future as many scenarios presented in Table 4 show a fuel price per passenger lower than the price of jet fuel.

There are also other aspects of flying that is not directly measurable in monetary terms, namely the environmental aspects of flying. By flying electric, emissions of greenhouse gases can be avoided. In Table 6, the details and specifics about the jet fuels current emissions can be seen as well as a calculation about the possible CO_2 emission savings in equation 3.

Table 6. Details about the environmental aspects of jet fuel.

Amount of CO2 in fuel	2,6 kg per litre	[56]
Sold fuel at airport	500 m3	[27]
CO2 emissions in Sweden from domestic flights	0,35 Mtonne	[57]

$$2{,}6\ kg\ per\ litre \times 500m3 \Rightarrow 1300\ tonne\ CO2 \Rightarrow \frac{1300}{350000} = 0{,}37\% \quad (3)$$

By replacing all traditional ICE aircrafts at Visby airport, the annual emissions from the domestic flights can be reduced by 0,37%. This might seem small, but Visby is only one airport and a rather small one. Large potential exists if multiple airports do the same. Visby airport also stands for 0,5% of Gotland's emissions right now [27]. This number can be reduced by implementing EAs at the airport.

5.5 Sensitivity analysis on the BESS

A sensitivity analysis on the size of the BESS has been made to understand how the BESS affects the total cost for 24 hours and how it affects the amount of electricity that needs to be purchased from the GEAB grid. The sensitivity analysis was done on the nighttime scenario with PV charging as it was the scenario with the lowest net energy use from the GEAB grid. The power flow for the scenario with a now doubled BESS capacity leads to a reduction in the amount of high power peaks compared to the original scenario shown in Figure 7. The net energy use is also reduced further from 3,72 MWh down to 3,01 MWh as the level of self-consumption of the PV electricity is increased further.

To further expand the sensitivity analysis, the size of the BESS was examined once more, now with its size halved. The power flow for this variation of the scenario leads to that the number of peaks is not reduced as the BESS does not have the ability to lower each peak. This leads to an increase in net energy use, from 3,72 MWh to 3,88 MWh as the self-consumption goes down.

Lastly, the sensitivity analysis examined the case where no BESS is present. This leads to no peaks being shaved but also no charging of the BESS, leading to more distribution of the PV electricity to the grid. However, the net energy use still increased to 4,40 MWh. How the different BESS sizes compare to each other and to the original setup in the nighttime PV scenario can be seen in Figure 13.

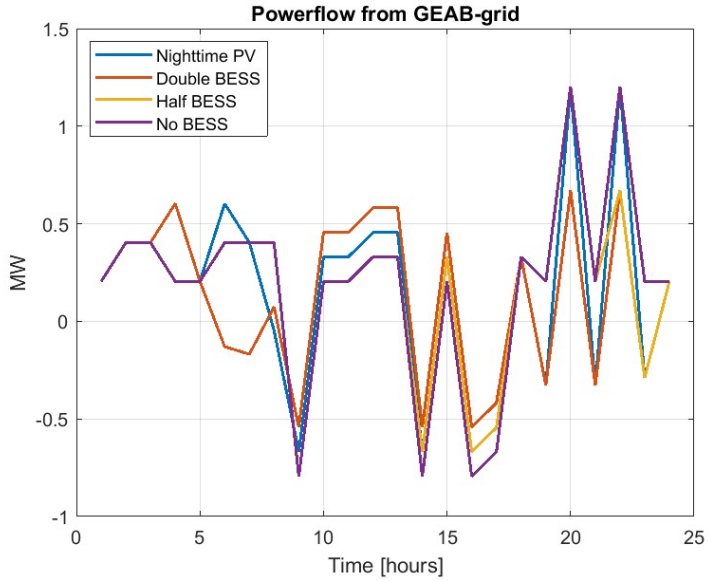

Figure 13. Power flow from GEAB with different BESS sizes and the original setup.

By then combining the power flow with the predicted prices for 2030, the cost for 24-hour operation during the 2nd of January, April, July and October for all the variations of the scenario are presented in Figure 14.

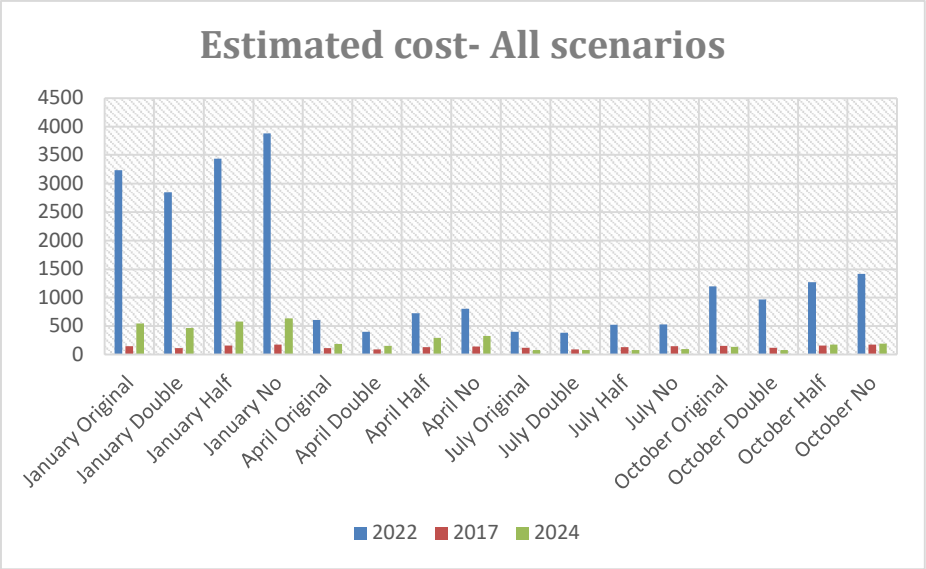

Figure 14. Estimated cost for 24-hour operation on the 2nd of January, April, July and October with the nighttime scenario with PV charging and different BESS setups.

6. Discussion

6.1 Challenges in electric aviation

One aspect of the transitioning to EAs in the future that is not taken into consideration in this study is the grade of transition. In this study, the examined case is in 2030 when all aircrafts are electrical meaning a transition from zero to a hundred with an overnight change from all ICE aircrafts to all EAs. It might be more realistic to have a gradually increasing transition with different shares of the aircraft fleet that is traditional ICE aircrafts and EAs. This would probably also result in a gradually increasing consumption of electricity at the airport that would be easier to facilitate and handle. The gradual transition is also easier and smoother from a financial perspective as large investments in charging infrastructure and new technology are unlikely to happen overnight. Regarding investments in infrastructure, one difficulty is the responsibility of financing the investment costs. Airports in Sweden are self-financing and governmental investments are not common. With that mindset, all the infrastructure and other changes to the airport grid will have to be paid for by the consumers, i.e. the passengers through ticket prices. This can probably lead to very expensive prices initially, which no one is prepared to pay. That is why this self-financing can be problematic in the beginning of the electric aviation's lifetime and a governmental involvement could be required to reach a commercial viability.

There are other difficulties with high power charging in the MW range at airports beyond getting access to power. Firstly, the cables must be thick to handle the power

and thereby quite heavy and hard to handle. Secondly, heat losses are also present when charging with these powers. Hence, the cable cannot be too long and must be cooled as well for optimal performance. Cooling is also necessary for the batteries when charging with powers in the MW range. Lastly, electromagnetic compatibility is also difficult as the high power chargers disturbs other systems at the airport such as air traffic control [18].

The global security situation is also something that affects the electric aviation environment, especially in Gotland as the island has always been a strategical point in military interests. By testing and implementing new technology at this already exposed area can be quite sensitive and maybe not in the governments and military's interest. As mentioned earlier, there is a military presence at Visby airport and with an increasing threat, big changes to the daily operations and infrastructure might not be reasonable.

One thing that is also important to consider is what development is actually desirable in Gotland. The demand is increasing in every sector, and the electricity is a limited quantity. Gotland is getting an increased power transfer in 2031 [22] but one still has to prioritize where the electricity will be used. In the further future, airports are expected to require a lot more power as the EAs are increasing in size and numbers. Therefore, the EAs at Visby airport might stand in the way for other developments that require more power. However, Visby airport is a medium sized airport and is not likely to be expanded largely due to the demand and proximity to the nearby city centre as a sharp increase in flying would probably not be approved as sounds and vibrations are present. This leads to that Visby airport might not be as much in the way for other developments as one could think. The ongoing project for 10 MW to the airport is more than necessary at the speaking moment, both in the simulation and in the reality, and therefore an increase to more than 10 MW is likely not credible. There is, however, a tangible increase in consumption if the EAs are present at the airport. In 2023, the airport consumed around 2,6 GWh [27] and if one adds the consumption that is necessary to charge the EAs, 1,46 GWh more are added which is an increase of almost 60%. This is a substantial increase in consumption, not as much as shown in [17] but still quite large and will have an impact on the local electricity situation. Before the implementation of EAs, the airport stood for 0,5% of the consumption in Visby. If one adds the aircrafts, this number increases to 0,9%. The consumption over a year is therefore not of great magnitude compared to the rest of the city but the power peaks is of more interest, especially if the demand of EAs increases even more.

6.2 Simulation and design of power grid

There are multiple aspects regarding the methodology that can have an impact on the results and how trustworthy the results are compared to the real-world situation. Firstly, the electrical grid has been model on a basic level and therefore does not contain multiple components that affects the power flow and how the grid must respond to different situations. One aspect is the form of electricity, in the simulation, AC has been

used as this is the normal form of electricity in the grid. However, batteries work on DC and the charging stations should therefore handle DC. This has been avoided due to numerical reasons as the usage of rectifiers have an impact on the simulation´s numerical outputs. The voltage level at 11 kV is therefore also questionable as this is not a commonly used voltage level in households. The reason for the choice was that a normal voltage level of 230/400 V is often not enough when dealing with high power loads as the current becomes a limiting factor. To optimize the simulation, one would have correct rectifiers and transformers to more clearly resemble the actual grid at the airport. This is not possible though as the design of the grid is a classified subject. By not including power electronics, transformers and other electrical components, the results become somewhat simplistic. Nonetheless, the intention was to visualize how the grid could be impacted rather than to perform a full electrical analysis which would require a more advanced simulation software. As such, the results presented here are deemed to be good enough to answer the question in hand. It should be noted however that components that were left out of the design would have an impact on reactive power that is ignored in the simulation and active losses in transforming steps which could have an impact on the results.

The BESS is also a component that is heavily simplified in the simulation as it only works as a switch between a generator and a load. This simplification still makes for a representative visualization of how the BESS works but due to numerical reasons, the charging and discharging of BESS does not match up completely. The control of how the BESS is being implemented is also something that could be further examined. In this project, no control algorithm is used for the BESS that optimizes the usage of it. Instead, the BESS is implemented as a support on the high power peaks when charging the planes and evaluated on how the utilization of the BESS impacts the net energy usage from the GEAB grid. The outcome could be altered if one decides to utilize the BESS on where it can be as cost effective as possible and not to optimize for self-consumption of PV electricity. This decision was made as the high power peaks are the times when the grid is most strained. It could be financially wiser to use the BESS differently, but this usage is of most kindness to the grid and therefore it was chosen. The utilization of the BESS could also be more examined in the way electricity is consumed from it. In the simulation, only full load is being examined and divided into individual full hours. With a more advanced control of the BESS, utilizing it with a lower power during other time periods than a full hour could possibly be beneficial.

How the PV is installed and supplying electricity is also something that could be discussed further. In the simulation, the PV is implemented as a full power generation for ten hours instead of a gradually increasing and decreasing curve that changes during the day. This was done to make numerical calculations simpler and more accurate as the total produced electricity is still the same, but the power curve differs. The impact of weather is also ignored and changes in solar radiation, shading and seasons can therefore have a large effect on the real results. This was ignored to keep the model as simple as possible and as the PV panels were modelled as a generator in Simulink. To

make the PV more realistic, a different software would have to be used with real weather simulations for Visby. The curve for production is estimated as an average between different seasons curves to get a simpler model [58]. By doing these simplifications, the production from the PV is probably exaggerated but the installed capacity is uncertain as there are multiple possible installation areas at the airport [44]. By having a larger PV installation compared to the one used in this project, this exaggerated productions impact on the simulation would be removed.

In the simulation, only large parts of the airports systems and components are included. These include the chargers, the terminal, the BESS and the PV and its connection to the GEAB grid. However, there are other smaller parts at an airport that require electricity that could have an impact on the demand and therefore the power flow to and from the airport. These components could be other vehicles that are being used at the airport such as electric cars that are charging at the airport, something that is being examined in [17], electric trucks that are used on the airside and in the operation. Lightning on the runways is also a large part along with communication, ventilation and heating and all of these are combined and put into the terminals load demand. This leads to not the most accurate variation in the load demand but still, by including all different parts, it leads to that with most certainty, the load demand of the airport is not zero even when it is closed for flying. However, due to numerical reasons, the value was set to zero to make the simulation simpler.

The demand of electric aircrafts and therefore the charging demand is something that contains uncertainties. The loadshape of the chargers was obtained by examining the current flight schedule and transforming the schedule to the smaller EAs. This is however perhaps not accurate. The goal is to increase flying as a mode of transportation to Gotland and therefore, the demand should be much higher. This is only a goal, and a larger market evaluation would have to be performed to obtain a broader picture of how many flights that are being handled at the airport in 2030. This is also a difficult task as 2030 is a long time away and no commercial EAs that are used in the simulation exist right now. Therefore, it was deemed simpler to work with the current flight schedule that does exist and not speculate to much about the future demand. When creating the loadshape, evaluation was made on full hours, and therefore a simplification regarding charging power was made. The power used in the simulation was 1 MW for one hour. This number could however be altered with a higher power used for a shorter time as described in [18]. In the future, even higher power could be actual but all of these numbers are speculations and therefore, it was simpler to use 1 MW for one hour as the battery in the electric aircrafts are assumed to be 1 MWh [18]. Many of these numbers could change, both up and down, which leads to the results being more of an illustration of what could happen and not an exact reflection of the reality.

The PV that is being used in the simulation creates periods during the day which lead to overproduction. Even in the scenario where the BESS is being charged with PV, overproduction is present as seen in Figure 7. During these hours, large amounts of

electricity is being sold to the grid and not stored for an increased self-consumption and thereby protecting itself from expensive power peaks in the future. To solve this, one could increase the BESS capacity as seen in the sensitivity analysis. Even by doubling the size of the BESS as seen in Figure 13, overproduction is still present. A larger BESS is expensive and would therefore perhaps not be the wisest choice. One option which has not been examined in this project is the making of hydrogen and using it in hydrogen fuelled aircrafts that are emerging [59]. By producing hydrogen with the overproduced PV electricity, one would receive a ready-to-go aircraft fuel that is easier to store than electricity. However, the efficiency in the transformations is low and therefore one would lose energy when creating the hydrogen. Hydrogen is also highly explosive and could be a security problem to have it stored at the airport. One other compelling reason against the production of hydrogen is the large need of pure water for the production [60]. Gotland has a major drinking-water deficit and therefore, it would be near impossible to produce large amounts of hydrogen on that site.

6.3 Economical aspects

When examining the results, it is important to take the findings with some caution as the presence of noise can alter the outcome. The estimated prices of electricity in 2030 in Figure 8, Figure 9 and Figure 10 all contains noise which lead to that the price for one day might not be representative of what is happening that week or month. By evaluating on the 2nd of January, April, July and October, it could be that the presented results are not representative of the behaviour in general of the electricity price which makes the comparison between the cost of different scenarios shown in Figure 11 and Figure 12 contain uncertainties. For example, if a peak value is present at night, it might be unfair to the scenario that charges overnight which is then debited largely. This scenario is, however, very possible as peaks in the price can happen anytime and anywhere due to unforeseen events or accidents for example. To get a fairer comparison and a fairer image of the behaviour of the price, it would perhaps be wise to use the mean price of each week or each month to reduce the impact of noise inflected peaks.

One aspect regarding the electricity price and the price for the 24-hour operation that has not been considered in this project is the presence of portfolio purchased electricity. Portfolio management works by purchasing large parts of electricity in advance and thereby getting rid of the impact of peaks and fluctuations in the price [61]. This is usually favourable for corporations that consumes large amounts of electricity such as an airport that charges EAs. This affects the results in this project by possibly reducing the impact of the peaks in the price in Figure 8, Figure 9 and Figure 10 and makes the mean value more interesting. To reduce the variability of the electricity price is of utmost importance to achieve stable and non-variable ticket prices. If one flight has been charged on a day when the electricity is basically free and one where the peaks are above 1000 EURO per MWh, the difference will be so distinct so the ticket prices will have to be affected. This is not good for the industry and the travellers as the economics about flying electric will be very uncertain. By using the portfolio management, this

difference and uncertainty has the possibility to be reduced or even completely removed which creates more stability for the industry.

6.4 Prediction of future electricity prices

Regarding the estimation of the future electricity prices, multiple simplifications has been made here as well. The major part is the design of the prediction model by using only one input which was the load demand. Many other factors influence how the price is set, such as transfer capacity, generation, type of generation, demand in other countries and electricity areas, world situation, the list goes on and on. This information would probably have been possible to obtain and use to train the prediction model as many of these factors have past data on hourly basis as the load demand and the price. However, how these factors will behave in 2030 is a lot harder to predict. The load demand for 2030 is something that has been talked about for a long time and therefore easier to predict. How other countries energy system topography will look in the future is difficult to foreseen and therefore, all other factors outside of the future demand was left out. These would most likely have an impact on the future price estimates shown in Figure 8, Figure 9 and Figure 10 but it´s difficult to assess in what way and therefore, the price forecasting part of the project is something that would have to be further researched. If further research on the subject would be performed, other model structures would most likely be beneficial such as a neural network to be able to handle the multiple inputs. If one would opt to go for the similar timeseries model like the ARMAX, other structures would be interesting to study such as SARIMAX which include seasonal variations and noise in its model structure. This model was not examined in this project as it is more complex and not compatible with the Ident App in the System Identification Toolbox in MATLAB.

Regarding the future load demand in SE3, in this project, the demand has been calculated as the industries further demand added to the demand in 2024. This means that other sectors possible increasing or decreasing demand has been ignored. This was done as the industries are the major part that will require more electricity in the future. The other sectors might also increase their demand but the consumption of electricity has been steady around 125 TWh in Sweden for the past 30 years [62] and have even begun to drop. This results in that only taking the industries future demand into consideration should be quite accurate.

The future of the electricity price is an uncertain subject as the energy system is rapidly changing and the world situation is constantly altering. That is why it is very hard to predict the future prices which is why this project has used three different scenarios based on different years in the past that all showed different characteristics and behaviour. Which of the three scenarios that are most likely to happen in 2030 is difficult to say and depends on many variables and factors that are all difficult to predict how they will develop over time such as transfer capacity, demand, new installation of production and also, energy wars and political views.

6.5 Environmental aspects and ticket prices

Regarding the future ticket prices, many additional expenses beyond just the fuel price decide the ticket prices. One part is the operating cost of the aircraft which include the price of the actual aircraft itself. EAs require more weight efficient material in its construction that are more expensive. This leads to a bigger construction cost as the fuselage becomes more expensive compared to traditional ICE aircrafts. The batteries are also a problematic area as they are expensive and more importantly, heavy. These problems with weight are the main reason why EAs are quite small compared to traditional aircrafts. All these aspects lead to a larger cost per passenger regarding construction which will have to be refunded somewhere, presumably by the ticket prices. So even though the electricity price per passenger as shown in Table 4 are competitive against jet fuel, the ticket prices might not be when all other cost aspects are added together.

In the results, shown in equation 3, the possibility of saving large quantities of CO_2 was presented. The main driver for electrification in all transport areas is the emissions of CO_2, which is true even for electric aviation but, there exists other emissions as well associated with flying. High altitude effects is something that is problematic in aviation as the emissions tend to stay at high altitude for a longer time period and thereby impacting the climate more by emissions of CO_2 and even water vapor [63], [64]. This is an extra factor why EAs are of interest as one removes the emissions and the extra impact of the emissions at high altitudes.

6.6 Sensitivity analysis

The sensitivity analysis examined different sizes of the BESS and how it affects the power flow and resulting cost of electricity. When having a large PV installation, it is important to be able to use your own product to optimize for cost efficiency [65]. By implementing a solar park of 1 MW and a BESS of 2,2 MWh, the self-consumption does not become large enough to limit the use of the GEAB grid and thereby, the cost. By doubling the size of the BESS, the self-consumption increases and the cost for the 24-hour operation was significantly lowered as seen in Figure 14. One interesting finding is that the size of the BESS impacts a lot if the capacity is increased but not so much if it is reduced or even removed as the no BESS variation in the sensitivity analysis still uses less net energy from GEAB than the daytime scenario which shows the importance of charging strategies and not only BESS size. This leads to a large potential to lower cost if the BESS size increases, probably even more cost reduction is possible than examined in the doubled BESS size case. But BESS are expensive and with an increasing BESS size comes an increasing cost for the BESS. The prices vary greatly but an estimate is around 1000 SEK per kWh [66]. The price is also predicted to be further lowered to 2030 [67] but there are still large investments regarding these energy storage systems and also, large BESS in greater ranges than the ones examined in this project can be difficult to manufacture as rare earth elements are a bottleneck.

The result of the sensitivity analysis also means that if investing in a larger BESS is not desirable, the loss is not that significant by simply skipping the usage of a BESS as the net energy use and 24-hour total cost did not increase that majorly. In April and July, the differences are even lower, and the differences are generally quite low if the focus is not on values from the 2022 estimation data. This concludes that there is a lot to gain by increasing the BESS but not a big loss by removing it.

6.7 Ethical aspects of electric aviation

One aspect regarding all electrification of the society including electric aviation is the ethics part. EAs driven by batteries are using a lot of rare earth elements that are hard to obtain in an ethical manner. The batteries need cobalt and lithium that exists mainly in Congo and the Andes. In Congo, child labour has a large presence, and, in the Andes, local habitants are being forced from their homes. Neodym, which is a rare earth element that is required in strong magnets for electric motors are mined in China and resulting in large local environmental impacts by radioactive slag heaps that are the results from the mining process. Many other materials are also required but almost all of them have one similarity, they exist in countries with questionable level of democracy. That is why people always must ask themselves before implementing these new technologies in our society, what the real impact is? Is it worth supporting questionable democracies just to fulfil our needs? Energy security wise, the electrification is not positive as it leads to dependencies on other countries which might not be desirable allies or business partners. EAs can reduce the climate impact regarding CO_2 emissions here in the west, but the effect on economic- and social sustainability must be examined further to really understand the impact on certain countries or people that a full transfer to electric aviation might lead to.

7. Conclusions

This project set out to explore how electric aviation can be utilized at Visby airport on the island of Gotland. The focus of the project has been on two major parts, the first being the electrical grid at the airport. By examining the power flow when implementing aircraft chargers, PV production, energy storage and then evaluating on a 24-hour simulation, it is possible to find out how high the power peaks are and how much electricity that must be purchased from the overhead GEAB grid. The second part was the estimation and prediction of the future electricity prices by training a linear model on past data of different characteristics. By then combining the two, the cost of a 24-hour operation evaluated on four different days during the year is obtained.

Four different scenarios were examined with different charging strategies for the aircrafts and different usage of the BESS. The results show that the nighttime scenarios were most cost effective as power peaks can be avoided by charging aircrafts slower overnight. The variation of the nighttime scenario that were most effective considering

cost was the PV variation, which made the BESS charging on only self-produced electricity. This variation was also the one that had the lowest net energy use from the grid and hence, not only being most cost effective but also kindest to the grid.

How the development of the price affects the choice of energy system at the airport is an interesting question. If the price follows the behaviour of the 2017 prediction with a very stable and low price, the BESS becomes obsolete as no need for peak shaving is presence and the cost savings of using more self-produced PV electricity becomes minimal with a low price of electricity. In that scenario, the BESS would probably be too expensive for what it can contribute with. However, this is only true if the grid has electricity to supply. If the demand is increased and the grid cannot supply, even with a low and stable price, the BESS becomes useful to help fulfil the airport's needs. The opposite situation appears if the prices become more like the 2022 prediction with a high mean and large fluctuations from day to day. Then, the BESS is of more use as it can help reduce the impact of high power peaks. This was examined in the sensitivity analysis when a double BESS capacity helped lower the cost even further, especially in the 2022 case.

Regarding the comparison between EAs and ICE aircrafts, the results show that the EAs can be competitive regarding fuel price. Every scenario of the four examined had variations that were more cost effective per passenger than the current jet fuel usage. It was mainly the 2022 estimates that could not keep up with the price of the jet fuel, but in the 2017 estimates and the majority of 2024 estimates, the difference in fuel price per passenger were substantial in the EAs favour. If one adds on the climate- and environmental impact, the implementation of EAs can help reduce the emissions of CO_2 and other greenhouse gases. It could also be possible that the reduction of CO_2 is something that can make the ticket prices more competitive as carbon taxes are being implemented throughout. The ticket prices are though hard to estimate as many other factors besides just the fuel cost makes up the ticket price in the end. In this area, more research is necessary to obtain a more thorough comparison between different aircraft types and thereby obtain a broader and more nuanced understanding if the EAs are competitive or not.

To conclude, it can be said that the subject of EAs is an exciting subject with a lot of different things happening around the world. It is, however, a young field that require more research to find out exactly how the EAs can operate optimally and thereby become competitive against the current ICE aircrafts. If EAs will be present in 5 years' time in 2030 at Visby airport is a difficult question to answer but, it is definitely an area where the island of Gotland has an opportunity as sustainable transport is one of their biggest challenges.

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Appendix

Below, the Simulink model can be viewed. The code used in the project along with the data can be found on GitHub: https://github.com/tnorstrom/VBY_grid.git