# Stockholm Arlanda Airport's opportunity to become the first hub handling battery-electric aircraft

Inventory of existing conditions and structured scenario sketching

Juliët de Cock • 500763407 • June 13th 2021, Amsterdam • Final version

Swedavia Airports

Amsterdam University of Applied Sciences

"*With Electric Aviation, we will be able to give more life to the whole of Sweden*"

*Maria Fiskerud,*
*Project manager Nordic Electric Aviation (NEA)*

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# Preface

This thesis 'Stockholm Arlanda Airport's opportunity to become the first hub to handle battery-electric aircraft' is written as a gradational research for Aviation Studies at the Amsterdam University of Applied Sciences.

The research has been assembled with Swedavia by reason of personal interest in the airport perspective in this drive of electric aircraft advancements. Swedavia has been greatly willing to involve me in their road to electric aircraft handling at Stockholm Arlanda Airport and introduced me to a large number of colleagues both within and outside of Swedavia. I was able to join the NEA working group and meet enthusiastic stakeholders in this field. The thesis research was an incredibly interesting process, both on a personal level due to the covid limitations, as well as the information I was able to work with. The willingness of the colleagues I got to talk with tackled both of the uncertainties for the covid situation limits, as well as yet unanswered questions. More of my personal experiences are described in Appendix I.

At first, I would like to thank my AUAS supervisor, Peter Jansen for his guidance, freedom in the research set-up and valuable time in this uncertain situation, even though the meetings were only held online.

Secondly, I would express my thanks to John Nilsson, who supervised me at Swedavia and took the time and extra effort to guide me, even in these times of reorganization. The weekly meetings and added introduction meetings with colleagues were of high value and gave me great insights in the current challenges and how to approach them in my thesis.

I want to take this last opportunity to again thank all the interviewees for their cooperation, even during the current covid situation and their busy schedules. This cooperation showed the amount of willingness that shapes the foundation of this new field.

I hope you enjoy your reading.

Juliët de Cock
Amsterdam
June 13th, 2021

# Executive summary

The battery-electric aircraft developments are gaining momentum and Swedavia wishes to accelerate research on the airport perspective. This research aims to gain insight in the required infrastructural adjustments for Stockholm Arlanda's airfield, and in which scenarios they need to be implemented.
Based on existing battery-electric aircraft developments and current work in this field, scenarios have been sketched for 2030, 2040 and 2050. The first scenario (2030) is based on 19-seater aircraft with 400 km range, scenario 2 (2040) considers 50-seater aircraft on a range of 1,000 km and the third scenario in 2050 looks at 100-seaters and 2,000 km range. Key factors like Arlanda airport's 2019 flight schedule data analysis and external factors have been identified and applied to these scenarios. Critical uncertainties have been pin-pointed, after which the final space requirements and electric aircraft placements are sketched.
The scenarios showed a big reliability on the battery technology and aircraft developments, as well as external factors which caused constraints for the scenarios to be expressed in actual numbers. However, the first key factors attained through flight schedule data-analysis, showed a low scenario, based on available seats, with 1 expected electric movement per hour and a high scenario, based on passenger demand, with 4 possible hourly movements in 2030. The 2040 low scenario also sketches 4 possible hourly electric movements, and 10 electric movements per hour in the high scenario. Lastly, the third scenario in 2050 showed a possibility of 12 hourly electric movements for the low scenario, and a high scenario of 26 electric movements per hour. Some of the main external factors influencing these numbers include the probability of the introduction of new routes or substitution of current routes, passenger demand fluctuations, the closing of Bromma airport, rail competition and the electricity grid challenges. Several infrastructural facilities are required to support the handling of electric aircraft, like fast-chargers, cooling equipment and battery storages. These facilities do not influence the airfield adjustments alone, as the safety requirements on aircraft charging, regarding hazard areas, make the aircraft placing dependable on the outcome of these concerns. However, two short-term placement options, one at Terminal 3 and one at the Northern remote aircraft stands can be located. For the long-term, these two options are joined by the third option at the current cargo handling area. Each of these options require further research and are dependable on several safety concerns.
Concluding, the introduction of electric aircraft will take flight soon and influence the airport airfield design in terms of peak power demands and infrastructural adjustments, where, especially in the beginning, investment costs will be the biggest hurdle. However, stakeholder willingness is greatly present in this field, which will be the starting point to handle with and overcome these first investment and circumstantial challenges.
Since critical uncertainties like battery technology and aircraft capacity developments, power demand capacities and infrastructural and safety dependencies influence the outcomes of the scenarios greatly, there is more research required on these topics to quantify the scenario numbers. To further identify the needed battery storage capacity and power supply, it is crucial for the airport to plan the (fast-) charging needs extensively according to the airlines' needed turnaround times. The next step would be to introduce battery packs (electricity storage) to cover the first peaks, followed by the installation of solar panels to generate energy during high production hours.
This thesis shows a welcome opportunity arising in this field, as there is a great amount of willingness from all stakeholders involved to overcome the many fragmented challenges. It is key to invest in this cooperation and start sharing and testing with all parties involved.

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# List of abbreviations

| Abbreviation | Definition |
| --- | --- |
| ARN | Stockholm Arlanda Airport |
| km | Kilometer |
| MW | MegaWatt |
| mWh | Mega Watt hour |
| Pax | Passengers |
| PSO | Public Service Obligation |
| PV | Photovoltaic |

# Definitions of terms

- **Battery storage**: a battery used for storing electrical energy
- **Battery pack**: see battery storage
- **Electrical aircraft**: overall term including battery-electric, hybrid, hydrogen and fuel-cell aircraft
- **Electric aircraft**: term used in this research to indicate battery-electric aircraft
- **Electricity grid**: network delivering electricity from producers to consumers
- **PV (photovoltaic)**: “PV in solar panels means ‘photovoltaic’, because the panel consist of small photovoltaic cells that are connected” (Greenmatch, 2021).
- **Power**: the process of supplying with electrical energy

# 1. Introduction

Over 200 project initiatives for electrified aircraft show us that this innovative segment is taking off rapidly. Both small start-up researchers as well as the well-known aircraft manufacturers Boeing and Airbus put their focus in this field, where one focusses on the development of an electrified aircraft in the shorter term, and the other has a more long-term (or visionary) approach. These developments have not been left unnoticed by the aviation industry, and especially not by the airport operators and their master planners. Swedavia's main airport Stockholm Arlanda (ARN) is one of these airports and sees the envisioned moment of operation of these aircraft rapidly come closer. Especially the terrain of commercial electrified aircraft is still in the starting phase of its development but is expected to have great influence on the airfield infrastructure needs. Swedavia, which is the licensed operator of ARN and nine other Swedish airports, wishes to accelerate the research on the airport perspective in this electrified aviation segment, which might hamper the overall progress of the initiative.

More focus on this airport perspective is needed to fulfill the wish to implement the electrified aviation developments. The airport plays a crucial role in this as it facilitates the aircraft handling at the airport. Therefore, future research is needed in this field as well. Where nowadays aviation stakeholders are working together to get electric aircraft in the air, the same should be done on electric aircraft handling: an electrified aircraft cannot take-off without the cooperation together with the stakeholders on the ground. Although these needs are relevant for airports all around the world, this research focusses on Swedavia's main airport: Stockholm Arlanda (ARN).

Various working groups recognize that the research made has been mostly focused on the development of aircrafts and there is a need to further analyze the infrastructural needs of airports. Small airports in the Swedish region are working together on creating test arenas for actual electric flights as well as the charging infrastructure. One of these airports is Åre Östersund airport, where Green Flyway is testing and reporting on the progress (Viklund, 2020). As every innovation starts small, this research starts with 2-seater electric aircraft and is a first step to the larger, commercial ambitions of ARN. The research done by Green Flyway has not been used as a source for this 5-month thesis research, but it has great potential to function as an important test arena in the coming months and years.

Even though nowadays only 2-seater electric aircraft can be seen up in the air, there is an ambition to have electric commuter or regional aircraft operational by 2025. 2025 lies in the very short term when compared to the 50-year visionary horizon that Swedavia's masterplan for Stockholm Arlanda Airport aims for. In that field, the master planning department of Swedavia has a need for an inventory of the near-term conditions in order to forecast the future of electrified traffic.

In this thesis, the key elements in master planning according to 'Airport Systems Planning, Design and Management' by Neufville and Odoni (de Neufville & Odoni, 2003) have been consulted. These are the following:

1. *Inventorying existing conditions*
2. *Forecasting future traffic*
3. *Determining facility requirements*
4. Developing several alternatives for comparative analysis
5. Selecting the most acceptable alternative as the master plan

The original intention of the research was to address the first three elements: inventory existing conditions, forecasting future traffic and determining facility requirements. However, after the first round of expert interviews, it became clear that the final step on facility requirements for

electric aircraft is not researched profoundly enough yet. Furthermore, thorough conversations with Swedavia have been held about the priority of the research, concluding to focus the research on the first two elements: inventory existing conditions and forecasting future traffic. For Swedavia, it is more valuable to include a scenario sketching process rather than a detailed analysis of the facility requirements. The third step can only be completed if the first two are finalized. Next to that, the scenario sketching took much more time than expected, therefore it was agreed to focus on step one and step two.
Even though the third step has been excluded from the project scope, a small set of information on the facility requirements has been collected through expert interviews and available literature review. This information can lay the foundations for further research for Swedavia or other stakeholders.

The first step includes a lay-out of the electrified aircraft developments in terms of flight range and passenger seat capacity, whereafter the scenarios can be sketched in step two according to the flight schedule. Experts' views, achieved through conferences, working group meetings and interviews, function as a final determination in the implementation of electrified aircraft handling needs at the airport's airside. These existing condition inventory, sketched scenarios and expert discussions finally feed the master planning to determine the future electric aircraft needs at Stockholm Arlanda Airport.

Taking the approach and the adjustments as described above into consideration, the aim of this research is to inventory the existing electrified aircraft conditions and forecast the future electrified traffic at Stockholm Arlanda Airport. Furthermore, the research will acknowledge which role Swedavia and Stockholm Arlanda Airport take in this electrified aviation segment. Finally, these points derive in the following main research question:

*"To what extent will the number of expected electric aircraft and their handling space requirements influence Stockholm Arlanda Airport's airside design?"*

To support this main research question, the following sub-research questions have been formulated:

1. What are the expected electric aircraft developments in 2030, 2040 and 2050?
2. What scenarios can be sketched according to the expected number of electric aircraft at Stockholm Arlanda Airport?
3. What infrastructural changes are needed to facilitate the electric aircraft handling at Stockholm Arlanda Airport?

The following background questions create a basic understanding about the research topic, thus provide knowledge to the sub-research questions and to better understand the main research question.

1. What has been done in similar industries or at other airports on charging electric (flying) vehicles and the corresponding safety risks/ analyses?
2. Who are the main stakeholders at Stockholm Arlanda Airport and what are their benefits in this development?
3. What are the master planning expansion steps at ARN until 2050?

Since many questions are still unanswered in this electrified aviation segment, the research scope given in table 1 is crucial to identify the parts that are included and excluded in the thesis research.

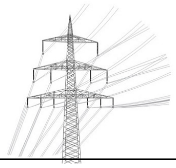
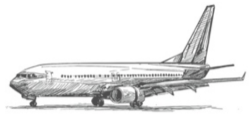
| <u>Out of scope</u><br>**Power grid ARN area** | <u>In scope</u><br>**Stockholm Arlanda Airport (ARN)** | <u>Out of scope</u><br>**Electric aircraft specifications and processes after off-block** |
|---|---|---|
|  |  |  |
| External factor analysis from landside, ARN's surrounding area or the electricity grid | Stockholm Arlanda Airport based movements and consequences for the airside | The movements (flight schedule) and consequences (airport infrastructure for electric aircraft) of any airport other than ARN |
| Local electric grid agreements or solutions for meeting the airport electricity demand | 100% battery-electric aircraft developments | Hybrid, fuel-cell or hydrogen aircraft developments |
| | Airport processes during the turn-around process of an electrified aircraft; | External factors during the flight steps outside the TAP (e.g. taxiing, take-off, flight, landing, over-night stays, maintenance) |
| | Analysis of the expected scenarios: short-term (2025-2030), mid-term (2040) and long-term (2050) | Any added time scenarios in addition to the ones in scope |
| | | Any other airport processes like maintenance or over-night stays |

*Table 1: Research scope*

In addition to the research scoping, it is important to determine the assumptions and limitations because a lot is still unknown. The following list provides insight in the made assumptions, thus scoping the project in more detail:

- The flight schedule used in chapter 5, on the scenario sketching, is an average week in September 2019. Swedavia's market analyst indicated that this week is representative for the first scenario in 2030. For the flight schedule of 2040 and 2050, the same week has been used to sketch the scenarios.
- The perspective for this research is solely the perspective of Stockholm Arlanda Airport. Therefore, the assumption is made that the airports that can be connected with electric aircraft, as displayed in the scenarios in chapter 5, are able to turn around the electric aircraft as well, thus being equipped with the required infrastructure and having the safety requirements in place.
- The calculated distances between Stockholm Arlanda Airport and the airport of departure/ arrival have been set on the great circle distance. Added safety distances have not been taken into account.
- This research has found optimistic views of the aircraft manufacturers, and partly has used that. However, the scenario for 2040 and 2050 have been adjusted due to the expert opinion that 100 and 186 passenger seats is too optimistic. Therefore, the numbers have been scaled down to 50 and 100 passenger seats.
- It is assumed that all routes had the same arrival and departure airports, so the so-called 'triangle routes' have not been considered in this research.

Next to the assumptions that need to be made due to this lack of information, there are also several limitations in the thesis. These limitations have influenced the research in a limiting way, but also have created opportunities. The limitations can be sorted in different categories: Covid-19 limitations and inexperience. Refer to table 2 for a further explanation, followed by the opportunities written below the table.

| Covid-19 | Inexperience |
|---|---|
| Reorganization: for Swedavia it was unavoidable to reorganize their teams, resulting in a reduction in the workforce and cost-saving plans which lead to a reduction of external projects or internal non-essential projects for the operational needs of the airport, thus creating new priorities for the remaining staff. | This e-flight segment is relatively new and currently only a 2-seater aircraft can be found in operation. A limited number of projects are testing their electrified aircraft, and there are even less projects now on the airport consequences due to the introduction of electrified aircraft. Therefore, the literature review and the experience of the experts is limited, whereas a certain information limit could appear. This means that the research can simply not be performed totally, thus creating the need to scope the project during the actual research. |
| On-hold e-flight projects: e-flight research projects have been put on hold due to the Covid-19 pandemic, therefore the progress in research is limited and less than expected. | |
| Master planning project on hold: due to the reorganization within Swedavia and the pandemic, the development of Stockholm Arlanda Airport's expansion steps have been put on hold. | |
| Way of working: The way of working has changed from on-site face-to-face contact to online meetings, mainly through Microsoft Teams. This caused a different way of communicating, which also has a risk of miscommunication due to the virtual interaction, internet connection (video calls are not always an option) and audio quality. | |

*Table 2: Thesis limitations*

As Table 2 shows, the research is influenced by some big limitations. However, these changes in working also created favorable opportunities.

- Online meetings create great opportunities to bring together experts all over the world, therefore, the interviews with several people from different places could be done during one week or even one day.
- The focus groups (also called focused group interviews) organized for the thesis were therefore possible to do, since every expert could join online, thus location constraints were no problem.
- Conferences, seminars and working groups organized by external organizations to bring together experts all around the world, became accessible to join from home. Therefore, valuable information and interesting discussions could be used as a source for this research.
- The absence of the need to travel to and from the office saved travel cost (for public transport, flights, car rides etc) and travel time, which could be invested in the research time itself.
- The final opportunity is that, even in changing times with great challenges, the situation allows to learn turning limitations into opportunities, like those stated above.

The thesis will start with literature review laying out the existing electric aircraft conditions and considering previous research methods applied to this field of work (chapter 2). The next

chapter is chapter 3, describing the methodology applied to the main research question and sub-research questions. This chapter describes the applied methods per chapter.
Chapter 4 includes the results, which is divided in the master planning elements as described earlier. Here, the inventory of the existing electric aircraft conditions can be found (chapter 4), as well as the scenario sketching analysis, thus the forecast of the electrified traffic (chapter 5) and the results on the infrastructural and space requirements at Stockholm Arlanda Airport (chapter 6). The final report conclusion can be found in chapter 7. Chapter 8 (discussion) considers the results gained in chapter 5 are put together and analyzed critically. The research is finalized with the recommendations, which are listed in chapter 9.

## 2. Literature review

2019 showed us over 200 projects on electric aircraft, which could be found all over the world.Initiatives on electric aviation that started with transporting two passengers, are now scaling up to carrying 6 to 19 passengers. These initiatives are started by many small companies and start-up businesses which are positioning themselves in the up to 19 seats segment (certified aircraft in in accordance with EASA regulations CS-23). Looking at the developments of larger electric aircraft, one can find mainly the major players like Airbus, Boeing and Embraer, as well as all the major engine manufacturers. Having these large players in this segment, it can be stated that the aviation industry sees a realistic future in electric aviation. Having said that, it is good to make a distinction in the feasibility and the size of the projects. Avinor states that the projects developing smaller electric aircraft, thus carrying less passengers and having a shorter range, can be put into a short-term vision, namely 2025-2030. The larger projects have been sharing to aim to be operational in 2040-2050. Besides manufacturers, airlines are also expressing their interest, and many airlines in the USA and Northern Europe (Widerøe, Logan Air, SAS, EasyJet, etc.) are in collaborative projects with aircraft and aircraft engine manufacturers (Avinor, 2020).

Take for example American Wright electric, who is collaborating with Easy Jet to develop an electric aircraft for 186 passengers, with an initial range of just over 500 km. Such a flight would, for example, be possible to use the London-Amsterdam route, which is one of the largest routes in Europe (reuters.com, 2020). In that embodiment, the goal is for it to be in service by 2030, but for long-term, the target is a range of 2,000 km.

Bauhaus Luftfahrt created an electric aircraft concept design called Ce-Liner with a range of 1667 kilometers and a number of seats of between 140 and 233, requiring an energy density of around 2000 Watt-hours per kilogram. The research organization shares their target to put this concept into operation is 2050 (Bauhaus Luftfahrt, 2020).

A project focusing on the shorter term, is the one from Heart Aerospace, aiming to deliver their ES- 19 aircraft carrying 19-passenger with 400 km range by 2026, to fly in Scandinavia. Even though the 400 km range sounds promising, Heart Aerospace mentions that the energy reserve requirements will provide a range in practice of 200-300 km (Heart Aerospace, 2021).

Another project that is already performing test flights is Israeli Eviation's electric aircraft called Alice. The last project aims to have nine passenger seats, a battery pack with a capacity of 900 kWh and a range of around 800 km. the aircraft can be found as of 2020 in Arizona, USA for testing and further development (Eviation, 2021).

Avinor states to believe that there are no unconquerable technological obstacles to developing electrified aircraft. Based on the existing technological knowledge and the expected pace of development, it should be technically possible to develop, certify and introduce aircraft carrying up to 19 passengers on regular civil scheduled flights from 2025–2030, and larger aircraft after that.

A feasibility study by Green Future AS on the electrification of Norway's aviation shows that more than 20 routes in the Norwegian short-haul network are suitable to be flown by electric aircraft, since their distances range from 38 – 170 km. They expect the first aircraft operating these routes would be a hybrid electric configured aircraft, nevertheless, in 10-15 years they expect that battery technology will offer sufficient capacity for 100% electric aircraft to operate flights of around 1 hour or more than 500 km. Norwegian policymakers have called for all short-haul flights to be electric by 2040. It is stated that it is not possible to shift the entire aviation industry to electricity, but it is expected that it may be possible for regional flights, general aviation and light aircraft to do so (Reimers, 2018).

Research done by Green Flyway, states that for the short-term electric aircraft developments, four different scenarios can be presented. These scenarios would include a range of 400 km and a maximum of 19 passenger seats. Two of the scenarios they sketched, the new possible short routes in general and new routes in the northern part of Sweden are kept out of scope. This research focuses on the possible electric flights at Stockholm Arlanda Airport, which is relevant for the two scenarios as listed below:

- Procured transport service, or the so-called Public Service Obligation (PSO) are routes that are maintained with the support of subsidies by the Swedish Transport Administration, offering a basic availability where airlines do not fly because these routes are not profitable. This low demand due to small populations also creates the opportunity for smaller electric aircraft (19 seaters) are able to operate on these routes. The following list shows the possible electric PSO routes connecting to Stockholm Arlanda Airport:
    - Torsby – Stockholm Arlanda
    - Hagfors – Stockholm Arlanda
    - Sveg – Stockholm Arlanda
- Existing domestic and foreign service: existing traffic from other regional airports is often served by aircraft with a capacity of more than 19 passengers, thus creating an uncertainty on the possibility of operating these routes with smaller electric aircraft. However, Green Flyway shared eight routes that could possibly become electric based on the range and current flight capacities. It is important to keep in mind that these routes are dependent on the unknown factors like the operating costs and the price of electric aircraft. The possible domestic/ foreign electric routes are:
    - Stockholm Arlanda – Sundsvall
    - Stockholm Arlanda – Trollhättan
    - Stockholm Arlanda – Jönköping
    - Stockholm Arlanda – Karlstad
    - Stockholm Arlanda – Mora
    - Stockholm Arlanda – Turku
    - Stockholm Arlanda – Oslo

Green Flyway states as well that four out of the seven procured routes by the Swedish Transport Administration can be flown by electric aircraft. It is good to state that this assumption is made pure from a capacity standpoint. Looking at the second scenario on the existing domestic and foreign routes, they state that eight routes would meet the maximum range of 400 km, including two foreign routes.

What is interesting, is that Green Flyway states that the longer-term scenarios with 190-seater aircraft and a range of over 1000 km would make it possible to replace roughly half of all routes worldwide by electric aircraft. For Sweden, this means that the whole of Sweden can be covered, as well as large parts of neighboring countries when departing from Stockholm Arlanda Airport. This would include Amsterdam Schiphol Airport and Prague international airport (Trafikanalys, 2020).

This literature shows the targets for short- and long-range electric flights. When looking at research question 2, on the expected electric aircraft at ARN, it can be concluded that a distinction can be made between a shorter term and long term. These results can function as a guideline to set up the expected flight scenarios, as shown in table 3.

| Year | Range [km] | Passenger seats [pax] |
|---|---|---|
| 2025/2030 | 500 | 19 |
| 2040 | 1000 | 100 |
| 2050 | 2000 | 186 |

*Table 3: Possible electric aircraft scenarios*

Having said that, figure 1, created by Green Future AS, gives a good overview of the electric aircraft scenarios.

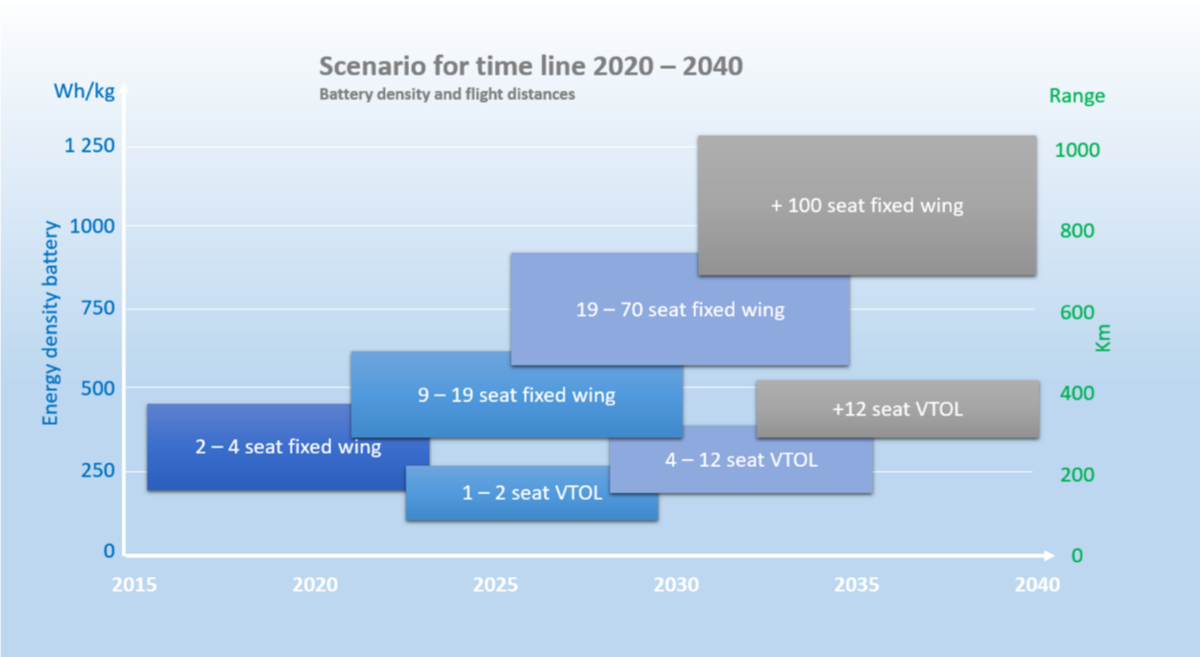



*Figure 1: Electric aircraft scenarios with reference to battery density and comparable range by Green Future AS*

Battery development

The automotive industry is one to lead the market on battery development. Seeing the expectations of this industry, the next generation battery will, instead of the currently known Lithium-ion battery with a density of about 400-450 Wh/kg, be developing into a solid-state lithium battery having a potential maximum energy density of just over 650 Wh/kg. However, the increasing investment in battery research and development makes predictions difficult. The expectation on the rate of gain of the energy density, is that it will remain on at least 8% per year. These battery developments will have a major impact on the range of electric aircraft, thus the number of electric aircraft at the airport as well as the total need for electricity through charging.

Here literature shows again that the range of the current battery technology with its certification standards shows us that aircraft with up to 19 seats and about 500 km range (effective range would be 350-400 due to energy reserve) is a realistic scenario to sketch (Reimers, 2018).

Charging electric aircraft

In order to support the first sub-research question on how to charge an electric aircraft, the following literature can be used as a basis, including research that has been done as well as the challenges and questions that are still relevant.

Research done by Green Flyway shows that there is currently no uniform standard for charging electric aircraft. However, a committee, “SAE International E40 Electrified Propulsion Committee”, has been set up in order to start on standardization work. They mention that for electric aircraft it will be for weight reasons and fast charging reasons necessary to charge with so-called "Mode 4 charge (DC)", which means that the electric aircraft is connected indirectly to the main power grid via a battery charger outside the aircraft for direct current (Trafikanalys, 2020).

Pipistrel, an aircraft manufacturer, is working together with Green Motion to develop a universal “Turnkey” charging technology in order to charge electric aircraft through a mobile battery bank or a fast charger linked directly to the electricity grid. The mobile charger normally requires a connection to a three- phase 400 Volt socket and somewhere between 16 and 32 Amps connection to the main electricity grid. The permanently installed fast charger requires the same amount of power of the mains connection as for electric cars (pipistrel-aircraft.com, 2020).

The Ce-Liner concept, as stated earlier on in the literature about electric aircraft development, is developed by Bauhaus Luftfahrt, who is working too on having exchangeable battery packs in order to comply with a 30-minute turnaround time (Bauhaus Luftfahrt, 2020).

When it comes to larger aircraft and thus larger engines and batteries, so will require charging in the Megawatt class, which places other demands on charging infrastructure. There is currently no standard designed here. In this area there are likely experiences to gain from Norway and how electric ferries are charged in connection with that located by land. Probably some form of power bank will be needed, which is regularly charged from the grid or from locally produced solar and wind power and is available to fast charge the aircraft batteries when needed (Trafikanalys, 2020).

Green Future AS' study on the effect of electric aviation on Norway shows that a 50-seater regional aircraft with a battery of 3,5MW may require an instant power of 10 MW for fast charging. It would therefore be the airport's choice to go with battery banks and charge from there, or instead to charge directly from the grid. A battery swap system in the aircraft would reduce the required level of instant grid power, since the charging of these batteries can be done over a longer period of time and during non-peak hours. Based on these assumptions, the power requirement from the grid per airport would probably lay in the range of 1 to 10 MW.

On the other hand, Heart Aerospace stated that, in order to be recharged within one hour, it would take 1 MW per 19-seater aircraft. Exact calculations on these requirements are hard to find, however, during the research phase, information gathered from electric aircraft manufacturers like Heart Aerospace ensures more insight in the charging needs.

Airport charging infrastructure

The following information on charging infrastructure shows the base of the question what charging infrastructure will be needed to implement at ARN. By benchmarking the charging infrastructure with other airports as well as other industries, a good overview can be given to form literature on the current developments and what would be optional to implement at Stockholm Arlanda Airport, or what to keep in mind during the developing phase.

In Sweden for example, Dala Airport, Mora Airport and Fyrstad Airport have installed a number charging stations for electric aircraft (Naturvårdsverket, 2020). The charging stations are of the same type as the standard chargers used to charge electric cars (Flygtorget.se, 2020) .

Going more north in Sweden, Swedavia chooses to use Åre Östersund Airport and Umeå Airport to test how an airport can meet the different needs of handling electric aircraft. In practice, this means that the airports deal with issues in an early stage like charging infrastructure, standards, power requirements, energy storage and power banks (perhaps mobile) and locally produced green electricity. In addition, Green Flyway takes part in this partnership to develop one unified charging standard (Trafikanalys, 2020). The municipality of Örnköldsvik will also test infrastructure at Örnsköldsvik Airport. In Norway, Avinor chose Röros Airport (probably also Trondheim Vaernes Airport) to install and test charging infrastructure. Looking at the connectivity between these test locations, it is easy to start up a new developed short-haul flight with 9 - 19 seats electric hybrid aircraft between all or some of these locations. The flight time between the towns would change between 30 minutes and an hour, which creates a very good availability (Trafikanalys, 2020).

These electric aircraft charging test locations are all in an early stage of problem solving, however, it is crucial to keep watching these developments and see what problems occur, as well as which problems are quicker to solve. These developments are currently not relatively comparable to operations at Stockholm Arlanda Airport, but the field research there can function as a base for process steps the bigger airports need to start with. These process steps they are working on are for example the charging infrastructure, turnaround time testing and safety aspects. More information on these processes and relevant steps gained through field research from for example Heart Aerospace can be found in the chapters 5 and 6. Heart Aerospace is a relevant stakeholder and source for this aspect, since they are participating in the research in this test arena, meanwhile developing their own 19-seater aircraft aiming to be operational in 2025. This can function as a relevance field research when combining the process steps at the smaller airports, whereafter to implement them to a bigger scale.

Next to Scandinavian airports, a Dutch initiative called 'Power Up' has started on researching the feasibility, potential and handling of electric flight within the Netherlands from 2026. With partners like Eindhoven airport, Rotterdam The Hague Airport and Groningen Airport Eelde, supported by Royal Schiphol Group and NLR – Royal Netherlands Aerospace centre, they have been joining forces to gain knowledge in creating charging systems. The goal of this initiative is to start with shorter flights with a maximum of 500 kilometres between Dutch airports and gain knowledge in these trials, where the intention is to start expanding to European airports in later phases and connecting to airports with a range of 1000 km.

Looking at the infrastructure aspects necessary for the different charging concepts as mentioned before (battery swapping, fast charging from batteries and directly from the grid), not only physical charging infrastructure is required. In order to safely handle for example, the swappable batteries, in-house charging facilities are needed, a designated space for safe battery storage as well as transport and lifting equipment to move batteries around safely. Looking at the connection between the grid or battery banks and the aircraft, specific equipment would be needed to establish safe connections. Naturally, all three options would require trained and dedicated personnel (Reimers, 2018).

Similarly, it is crucial for an airport to take into consideration that the needed amount of electricity might exceed the current electricity capacity, especially during peak hours. Therefore, infrastructure is needed to store larger amounts of electricity in larger battery or power banks. This infrastructure would include parts such as remote batteries and increased transmissions lines. The research will show if storage is necessary according to the electricity needs, and if so, it is important to decide on the storage capacity. Background question 2 will focus on benchmarking storage possibilities, parties that will be interesting would be Tesla with their Megapack in Australia with 129MWh capacity delivering over 100MW power, Fluence which a Siemens and AES company, is a global leader in the market for utility-scale energy storage technology, Siemens and their electric aviation developments. Also, where benchmarking will be done on charging steps in background question 1, these industries could be a good first step to look into, since electric ferries are also charged from stationary packages. The electric heavy truck industry might be closest to the developments needed for electric aircraft charging. Research is being done on projects to charge trucks with more than 1 MW, which is similar to the expectations from Heart Aerospace's 19-seater aircraft, needing 1 MW to be charged. NREL is performing this research right now, on charging medium- and heavy- duty electric vehicles (NREL, 2021).

If storage will be needed in certain scenarios, the options whether this storage can be done on airside or landside needs to be analyzed. Storing big amounts of energy at airside brings safety concerns, as well as infrastructural impacts on the space available. Therefore, existing airport regulations need to be consulted, which will be retrieved from Transportstyrelsen, the responsible party for drawing up regulations and ensuring that they are abided by authorities, companies, organizations and citizens (Transportstyrelsen, 2021).

<u>Safety considerations</u>
Swedavia mentions that new safety requirements need to be taken into consideration in order to charge of electric aircraft at the airport. This means that it is crucial to look at what the safety

aspects are of charging an electric aircraft next to a kerosene aircraft. In order to mitigate these risks, they suggest procedures like isolating fuel vapours from electric sparks and implement new firefighting capabilities when batteries catch fire. Again, the appropriate training and equipment needs to be in place here in order to maintain the same safety levels as those into place with kerosene aircraft.

In addition to the safety requirements on charging an electric aircraft next to a fuelled aircraft, safety procedures need to be put into place in order to safely replace batteries as well as charge batteries onsite. Again, appropriate infrastructure to store, charge and handle batteries is crucial to implement.

In order to work on the sub-research question on the space requirements at the airport, more research needs to be done on safety and physical space through interviews with manufacturers and experts. The data collected from these interviews, as well as documents that might be shared as background information are highly valuable for further research.

# 3. Methodology

This research methodology describes the methods and specific procedures used for collecting and analysing data with the goal to give answer to the research question for this research. The methodology will include data collection and data analysis, for both qualitative and quantitative research.

The main research question, "*To what extent will the number of expected electric aircraft and their handling space requirements influence Stockholm Arlanda Airport's airside design?"* is a question that needs literature and technological research, as well as input from experts' opinions on this matter, since it is a question requiring future visions supported by expert experience.

Figure 2 is used in every chapter to identify the different phases of the research, thus which information can be found to support the final main research question. As mentioned in chapter 1 on the thesis introduction, the first step for this research starts with an inventory of the existing conditions, followed by forecasting future traffic through scenario sketching. The determination of the facility requirements can be found in the part on the airport infrastructure. The willingness of the stakeholders is the final, meanwhile crucial, part in answering the main research question.

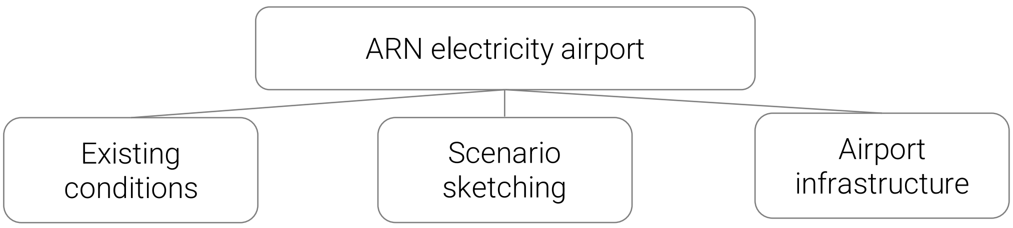



*Figure 2: Research set-up*

Table 4 clarifies the research approach per sub-research question. These approaches will be further addressed in the parts below the table.

| Sub-research question | Approach |
|---|---|
| What are the expected electric aircraft developments in 2030, 2040 and 2050? | Qualitative field research: interviews<br>Qualitative desk research: literature review |
| What scenarios can be sketched according to the expected number of electric aircraft at Stockholm Arlanda Airport? | Quantitative desk research: flight schedule data analyzation<br>Qualitative field research: interviews<br>Qualitative desk research: literature review |
| What infrastructural changes are needed to facilitate the electric aircraft handling at Stockholm Arlanda Airport? | Qualitative field research: interviews<br>Qualitative desk research: literature review |

*Table 4: Research approach per sub-research question*

*Sub-research question 1: What are the expected electric aircraft developments in 2030, 2040 and 2050?*
This first sub-research question is answered by conducting desk research through literature review and online conferences on the current aircraft developments and their aim to be in operation. Desk research will also be performed on the existing conditions related to these aircraft developments, in terms of standardization and infrastructural developments. These developments will be discussed in the interviews, to validate the results with experts in the electric aviation field. Finally, focused group interviews will function as a moment of discussion and validation on this gathered data.

*Sub-research question 2: What scenarios can be sketched according to the expected number of electric aircraft at Stockholm Arlanda Airport?*
This sub-research question firstly conducts information through quantitative desk research on the data analysis of Stockholm Arlanda Airport's flight schedule. The aircraft specifications from sub-research question 1 gained through literature review are applied on the schedule, after which the scenarios can be sketched. Three key factors are applied to the data, which are a range filter, available seats filter and passenger demand filter. For this sub-research question, semi-structured interviews and focused group interviews are conducted to gain expert opinions on the scenarios sketched, external factors and critical uncertainties, as well as to validated or discuss the scenarios and form recommendations for further research. Qualitative desk research was gained through information shared in working groups and online conferences as well.

*Sub-research question 3: What infrastructural changes are needed to facilitate the electric aircraft handling at Stockholm Arlanda Airport?*
The final sub-research question collects data on the required electric aircraft infrastructure and current standardization and certification processes through literature review, working groups and online conferences in qualitative desk research. Semi-structured interviews conducted as qualitative field research will add data on the current research, as these interviews are done with stakeholders from various perspectives in this segment. The interviews have the aim to collect main issues encountered to apply for the decision making of the placement of the electric aircraft. Lastly, a focused group interview together with several experts in the field will function as a moment for discussion of the space requirements, as well as a validation of the outcomes and a moment for adding recommendations for further research.

To maintain research validity and transparency for follow-up research, the conducted interviews (table 5) have been coded to validate the research outcomes in the chapters 4, 5 and 6. The focused group interview indications have been added to this list as well, with the abbreviation FGS for Focus Group Scenario sketching and FGE for Focus Group Electricity storage.

To ensure reliability and trustworthiness of both the semi-structured and focused group interviews, the following criteria have been set up in advance to collect valid data needed for the research questions:

- Interviews will be held with experts working on topics that are corresponding with the objective of the research questions, whether this is related to Swedavia's processes at ARN or in the electric aviation field. If a question is left unanswered or unsure, the answer will either be asked to another expert, or the question will be left unanswered and added to the recommendations for further required research.
- To ensure answer outcomes from the entire field and counter blind spots in the research, interviews will be held, with experts from all field perspectives, like the airport operations, energy management, safety agency, airline, and aircraft manufacturer perspective.
- On forehand, the project scope and the problem statement are explained clearly in order to prevent confusion between the interviewee and interviewer on the meaning of the research concepts.
- With permission of the interviewee, the interview will be recorded, to transcribe the statements correctly and complete. The statements will be checked with the interviewee afterwards if he or she agrees with the information transcribed. The usage of names and job titles in this thesis will be checked with the interviewees as well.
- The questions asked and answered during the individual interviews will be discussed during the focus group with 5-6 experts, in order to discuss the validity of the answer and if there are any uncertainties and if the answer is reliable. The two focus groups discuss found statements during the research, where one focus group pinpoints the

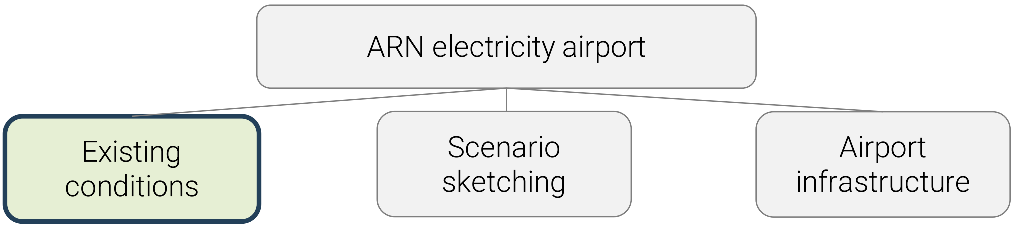
scenario sketching outcomes, and the other challenges on the electricity storage and electricity needs.

| Code | Date of interview | Name | Role |
|---|---|---|---|
| AA1 | May 11th, 2021 | Anna Arvidsson | Master planning Stockholm Arlanda Airport |
| GB1 | May 4th, 2021 (FGS) | Geert Boosten | Board member DEAC and Professor aviation management |
| HA1 | March 18th, 2021<br>May 4th, 2021 (FGS, FGE) | Hampus Alfredsson | RISE Researcher electromobility |
| HL1 | March 4th, 2021 | Henrik Littorin | Consultant electric flight |
| HP1 | February 23rd, 2021<br>May 4th, 2021 (FGE) | Håkan Pedersen | Swedavia energy |
| JN1 | Company supervisor, weekly meetings<br>May 4th, 2021 (FGS, FGE) | John Nilsson | Swedavia strategic manager electric and hydrogen aviation and infrastructure strategic planner |
| JN2 | March 18th, 2021<br>May 4th, 2021 (FGS, FGE) | Joakim Nyman | RISE Researcher electromobility |
| JT1 | March 9th, 2021<br>May 4th, 2021 (FGS) | Joacim Thelin | Swedavia Market analyst |
| MF1 | March 9th, 2021<br>May 4th, 2021 (FGS, FGE) | Maria Fiskerud | NEA project manager |
| MP1 | April 29th, 2021<br>May 4th, 2021 (FGS, FGE) | Martin Porsgaard | NISA director |
| MT1 | April 15th, 2021 | Mari Torstensson | Green airports project manager |
| OL1 | April 20th, 2021 | Olav Larssen | Head of Avinor carbon reduction program |
| PO1 | April 15th, 2021<br>May 4th, 2021 (FGE) | Patrik Ollas | PhD student at RISE |

*Table 5: Conducted interviews and linked codes*

Due to time constraints and busy schedules, the direct perspective of the aircraft manufacturer and airline were not able to be included in this research. Fortunately, during Nordic network for Electric Aviation (NEA) working groups, information could be gathered on these perspectives, since aircraft manufacturer Heart Aerospace and airlines like SAS, Iceland Air, Bra Air and Finnair, were part of the working group and presented their current work in the electric aviation segment. In addition to the working groups, answers on direct questions related to the research were gained through e-mail.

# 4. Results: existing conditions




As the structure in the introduction indicated, the research results start with the existing electric aircraft conditions. This chapter will start with the existing developments of battery electric aircraft, followed by the ongoing projects on electric aviation in the Nordics.

## *4.1. Electric aircraft technologies*

As the literature review indicated in chapter 2, there is a lot of investment in battery-electric aircraft developments. Two main technologies can be distinguished: fast-charging and battery-swap aircraft. During this thesis research, conferences and interviews indicated that the battery-swapping technologies are not the main technology that is invested in today. As Littorin (personal communication March 4$^{th}$, 2021) mentions, it is more likely to see fast charging technology than battery swapping due to the handling safety. Battery swapping requires heavy equipment, in terms of batteries. The connecting points between the batteries and aircraft system, and batteries and charging system, will be used a lot due to the frequent battery swapping which can cause safety issues like ignition sparks, breakdown of connectors or worse. In addition to that, for smaller aircraft it is not likely to have battery swapping systems due to weight issues. The fast-charging technology creates weight balance in the aircraft, since the batteries can be spread out more evenly throughout the body, where the swappable batteries have a limited space to be stored (personal communication March 4$^{th}$, 2021). Therefore, this research focuses on fast-charging electric aircraft technologies when sketching the scenarios (chapter 5), electricity needs (chapter 5, section 5.9.) and the airport infrastructure consequences (chapter 6). Nevertheless, this technology remains an option, but further research is required. Questions that are still unanswered but vital to consider, are related to for example the logistics of this technology, to have a total network perspective and anticipate on the location of the batteries in the network and where they can be charged (GB1).

## *4.2. Ongoing projects on electric aviation in the Nordics*

Electric aviation is a hot topic these days, and next to the many on-going projects by aircraft manufacturers, several working groups can be distinguished nowadays. One point which is vital to mention before diving into this sub-chapter, is that the working groups specified here are just a small part of al the research groups going on. These were the working groups relevant for this research, but it is just a start.

### **4.2.1. NEA: Nordic network for Electric Aviation**

The Nordic Network for Electric Aviation (NEA) is a platform funded by Nordic Innovation, bringing together Nordic stakeholders related to or interested in the electric aviation segment to speed up the introduction of electric aviation in the Nordic countries. Twelve partners from six Nordic countries are working together on this project. Some of these partners are the airlines SAS, Iceland Air, Bra Air and Finnair. The airport operators like Avinor and Swedavia are included too, as well as electric aircraft manufacturer Heart Aerospace and research centers RISE (Research Institutes of Sweden) and NISA (Nordic Initiative for Sustainable Aviation). NEA has set four objectives (Fossil-free aviation 2045, 2021):

- Standardize the infrastructure for electric flights in the Nordic countries

- Develop business models for regional point-to-point connections between the Nordic countries
- Develop aircraft technology for Nordic weather conditions
- Create a platform for European and global collaboration

#### 4.2.2. Research Institutes of Sweden (RISE)

RISE Research institutes of Sweden is Sweden's research institute and innovation partner. International cooperation between the industry, academia and the public sector ensures the business competitiveness and contribution to a sustainable society (RISE, 2021). One of the many research projects RISE is working on, is MODELflyg which is an infrastructure modelling project for a large-scale introduction of electric aircraft and air traffic control. "The project intends to create conditions for battery-electric aviation as one of the pieces of the puzzle for a sustainable and accessible flight, partly through an in-depth modelling study where actual flight data is used to develop an analysis tool for electrification of various air transport flows, but also from an air traffic control perspective" (RISE, 2021). Next to this project, they are researching and reporting on the implementation of Solar PVs at the airport (PO1, MF1), more on this challenge can be found in chapter 5 section 5.9. about electricity needs.

#### 4.2.3. Green Flyway

Green Flyway is a collaborative research project with a test arena (figure 3) for electric test flights between the Norwegian Røros Airport and Swedishs airports Åre Östersund Airport and Härjedalen Sveg Airport. In addition to the test arena, there are existing infrastructure facilities testing the charging process and the infrastructural needs for an airport (Green Flyway, 2021).

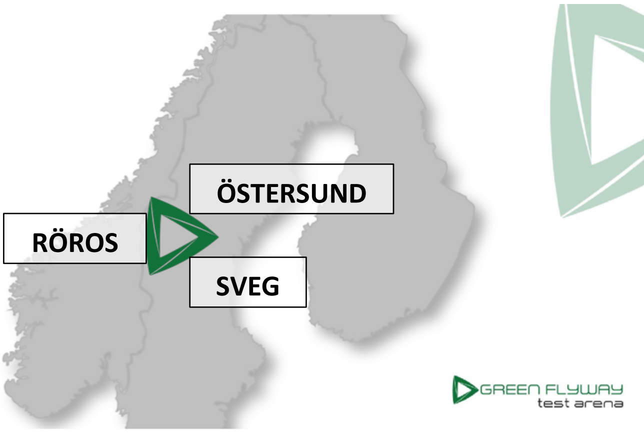
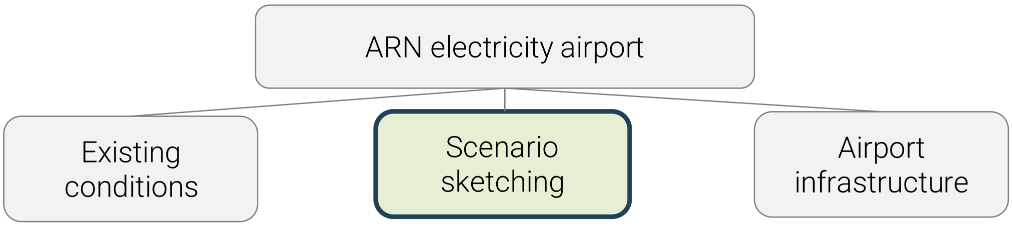



*Figure 3: Green Flyway test arena (Source: GreenFlyway)*

#### 4.2.4. Electric Air Transport in Sweden (ELISE)

The purpose of the project Electric Air Transport in Sweden (ELISE) is to coordinate development and use of electric aircraft in Sweden. Their goal is to establish a Swedish based electric aviation industry, seeing the first electric aircrafts in operation in 2025 and to build world-leading research for the next generation of electric aviation. Organizational partners are amongst others RISE Research Institutes of Sweden and several Swedish universities. The project started on January 1st, 2020, and will end the 19th of January 2022 (Chalmers, 2020).

# 5. Results: The scenarios




As a result of the upcoming electric aircraft developments, as shown in chapter 4 about the existing conditions, chapter 5, section 5.1., 5.2. and 5.3. sketch scenarios based on Stockholm Arlanda Airport's flight schedule data to identify what the relevance of the introduction of electric aircraft will be for Stockholm Arlanda Airport, resulting in chapter 6 on the needed airport infrastructure changes and the speed in which Swedavia can expect those. These scenarios are all based on Stockholm Arlanda Airport's flight schedule in a regular week in September 2019, which would function as a good base for the time phases that will be mentioned later in this introduction (personal communication, March 9th, 2021).

The focal issue, namely the electric aircraft relevance at ARN, is the first step of the scenario sketching. However, to sketch the impact of the aircraft, key factors functioning as filters should be considered to create a plausible scenario sketching process. As pointed out in chapter 2, the ranges and passenger seats of electric aircraft will differ from existing jet-fuel aircraft specifications.

A limit in range and seats causes a change in the routes that can be operated from Stockholm Arlanda Airport, since electric aircraft do not have the range to reach all existing destinations like regular aircraft do. In addition to that, the difference in passenger demand influences the routes since it is economically not feasible for airlines to operate with smaller aircraft on routes with a higher passenger demand. Therefore, filters are applied on the flight schedule data to sketch the extent of the flight replacement, thus impact of electric aircraft at the airport. In addition to the existing aircraft seat capacities, the load factor is considered to cover the passenger demand on those flights, as the existing routes might be operated with a larger aircraft than the passenger demand requires. This changes the feasibility, thus probability, for an electric aircraft to operate on the lower demand routes with a lower seat capacity. Considering these key factors, the most plausible scenarios will be sketched applying the following three filters:

1. Range filter: Expected electric aircraft range, which is based on the great circle distance, thus excludes any required reserves or flight paths that increase the flight range.
2. Passenger filter: Expected passenger demand, sketching a high scenario.
3. Seats filter: Expected number of electric aircraft passenger seats, sketching a low scenario.

As the literature review indicated in chapter 2, several aircraft developments can be expected over short-, medium-, and long-term time phases. Table 3 and figure 1 in chapter 2 indicate electric aircraft developments for the terms 2030, 2040 and 2050. The first time phase is 2030, which will be the base for the first scenario, in which literature shows a range of 500 km with a capacity of 19 passenger seats. Conducted interviews and working groups during the research argued that it is more feasible to work with a range of 400 km due to current battery developments, which is why this will be the range filter applied in the first scenario. The expected 19 passenger seats are applied as seats and passenger filter.
For the second scenario, the time phase for 2040 is considered. Here, literature shows an expected range of 1000 km and a passenger seat capacity of 100. However, during the interviews and focused group interviews with electric aviation experts, the assumption for 100

seats changed to 50 seats in the second scenario. More on this decision can be found in chapter 5.2.
The final scenario, scenario 3, includes the time frame for 2050. Literature shows the aim of having electric aircraft with 2000 km range and a capacity of 186 passenger seats. Here, as well as in the second scenario, it is expected by experts to have smaller aircraft, thus the seat capacity is adjusted to 100 seats.

Since not only a technical analysis is enough to sketch the most plausible scenarios, sections 5.4. (Turnaround times), 5.5. (Airline network developments), 5.6. (PSO routes), 5.7. (Bromma airport), 5.8. (Competition air and rail) show the external factors influencing the amount of expected electrified routes. Section 5.9. includes information on the electricity needs per scenario, where section 5.10. analyzes the preceding factors and discusses the sensitivity of the scenarios.

Together with experts' opinions gathered from interviews, conferences and working groups, the expected electric aircraft demand and external factors influencing the increase or decrease in routes from and to Stockholm Arlanda Airport are drawn. This information provides insight for Swedavia's master plan on the expected infrastructure capacity and the required speed of implementation.

## *5.1. Scenario 1: Electric 19-seater aircraft with 400 km range*

The first scenario is based on the market expectations of a 19-seater with 400 km range in 2030, as well as the rapid developments of the Swedish Heart Aerospace ES-19 aircraft (HL1, MF1). The aircraft of Heart Aerospace is expected to be certified and ready for operation in 2026, but since it is expected that this introduction would take more time to really start operating, the time frame for this scenario has been set on 2030 (OL1). To sketch the impact of this scenario for Stockholm Arlanda Airport, a division has been made between the steps of a range filter, followed by a seats and a passenger filter. The range filter of 400 km has been applied to the flight schedule, on which the high and the low scenario have been applied. With 613 possible movements divided over 15 destinations, it functions as a base to further narrow down the electric routes according to the passenger demand and available seats filters into a plausible 2030 scenario. The seats filter is a low scenario which is based on the actual available seats according to the flight schedule data provided by Swedavia. The next filter, the passenger filter, demonstrates a high scenario as it applies the passenger load factor on the routes, and does not filter out the routes which were limited in the low scenario (seats filter) due to larger aircraft capacities.

### 5.1.1. High scenario 1: 19 passenger filter

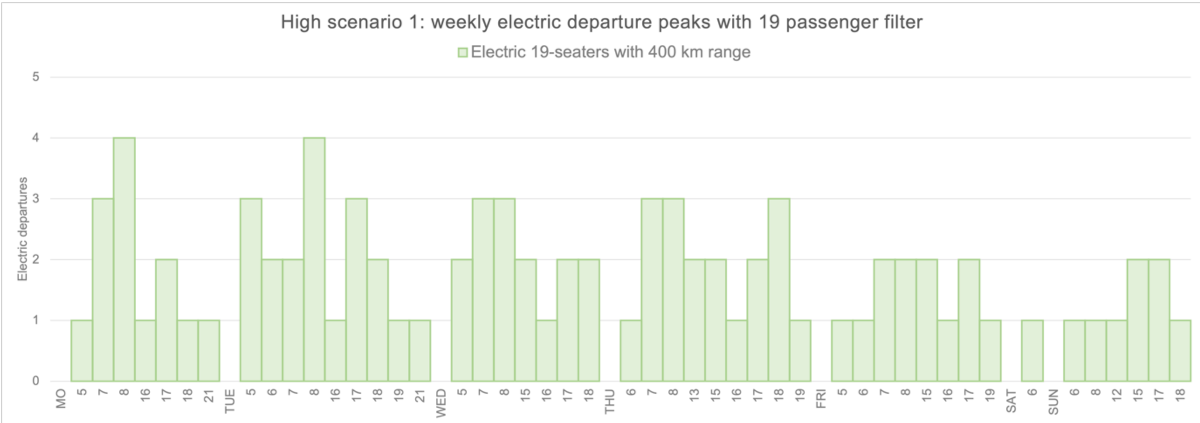
This high scenario considers routes that could be operated on a range of 400 km with smaller electric aircraft, according to the load factor: the passenger filter. The results of this filter can be found in table 6, which shows 86 weekly electric departing movements divided over 13 destinations.

| | High scenario: 19 passenger filter |
|---|---|
| Movements [per week] | 86 |
| Peak movements [per hour] | 4 |
| Destinations [per week] | 13 |

*Table 6: High scenario 1 electric movements and destinations*

Due to confidentiality reasons, the specific destinations cannot be shown in this report. However, it is essential to include these results in the scenario sketching, since the number of possible electric movements and reachable destinations increase the feasibility of the scenario, thus influence the required speed of infrastructure implementation at Stockholm Arlanda Airport.

Graph 1 illustrates the electric departing movements the airport would see with electric aircraft with 400 km range and 19 passenger seats, based on the passenger demand. The data as illustrated in graph 1 indicates that this high scenario would have peaks of 3 and 4 electric aircraft per hour, mainly in the morning and late afternoon.




*Graph 1: Weekly electric departure peaks high scenario 1*

The movements identified through this filter are not seat capacities of 19 seats or lower, thus could only be replaced if the airline decides to lower the available capacity on this route. The passenger demand is a factor that changes frequently. Therefore, further in-depth research and thorough communication with airlines is necessary to portray the actual expected electric aircraft movements.

### 5.1.2. Low scenario 1: 19 seats filter

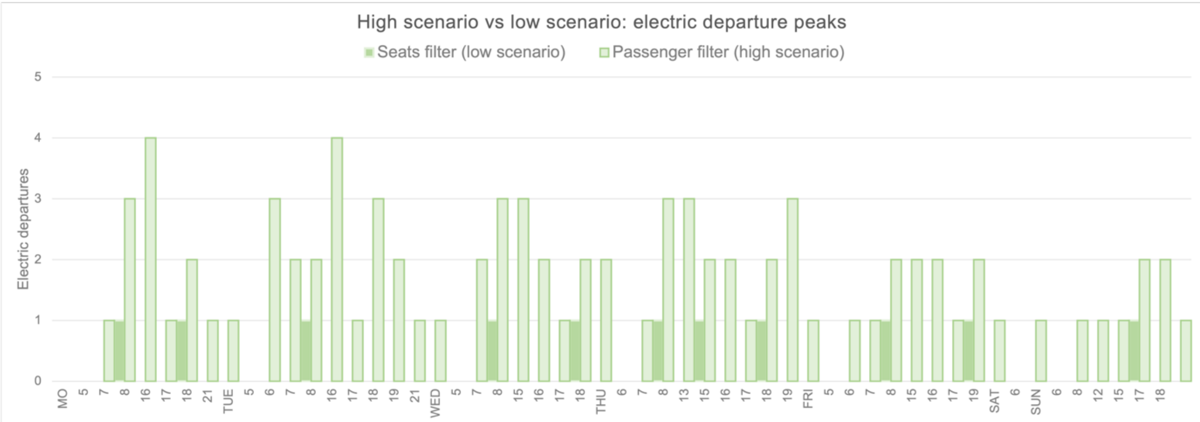
On top of the range and the passenger demand filter, this seats filter sketches a low scenario. Here, the 19-seats number is applied on the current aircraft operating on the routes with 400 km range. The destinations and movements shown in this scenario are flights that can be replaced with electric aircraft without lowering the current seat capacities, like section 5.1.1. discussed. When applying this filter, the number of possible electric movements is significantly reduced from 86 to 11, with only one destination to be reached. Figure 4 shows the possible destination to be operated by electric aircraft, as table 7 elaborates on the number of movements as well.


*Figure 4: ARN's electric destinations with 400 range and 19 seats filter*

| IATA Airport | Airport name | Country | Movements [per week] | Range [km] |
|---|---|---|---|---|
| EVG | Härjedalen Sveg Airport | Sweden | 11 | 328 |

*Table 7: Low scenario 1 destination, movements and range*

For the airport, it is important to be aware of the expected peak moments to understand the number of aircraft arriving at the same time, later resulting in the related fast charging and power demand consequences during their turnaround process (refer to section 5.9. for more information on power demand and electricity needs). Graph 2 shows the departure times and peaks of the possible electric aircraft, from which the low scenario sees a maximum of one electric aircraft per hour and two per day, mainly in the morning and one in the late afternoon.




*Graph 2: Weekly electric departure peaks high vs low scenario 1*

Table 8 indicates the difference during the high and low scenario, thus the consequences for the master planning when looking at the different filters.

| | High scenario: 19 passenger filter | Low scenario: 19 seats filter |
|---|---|---|
| Movements [per week] | 86 | 11 |
| Peak movements [per hour] | 4 | 1 |
| Destinations [per week] | 13 | 1 |

*Table 8: High scenario 1 and low scenario 1 electric movements and destinations*

## 5.2. Scenario 2: Electric 50-seater aircraft with 1000 km range

This second scenario is based on a 50-seater electric aircraft with a range of 1,000 km. Literature has shown that aircraft manufacturers aim for a 1,000 km aircraft in 2040 with a seating capacity of 100 passengers. However, interviews and attended working groups indicated that this is a notably optimistic approach, whereafter the decision has been made to apply 1,000 km range and 50 seats capacity filters. The reason to decrease in seats instead of range, is because it is more likely to see smaller aircraft on longer range rather than larger aircraft on shorter ranges, especially in the Nordics (MF1, HL1).

The scenarios and timeframes after 2030 become more of a visionary scenario since the main research focus is now on the first step: to develop the first 19-seater aircraft to be in operation between 2025 and 2030. From then on, aircraft manufacturers will need to learn about scaling up based on these operations, battery development and overall technology improvement (HL1).

Applying the 1,000 km range filter on the flight schedule data, 43 destinations can be reached with 1,000 km range electric aircraft, and 1,391 departing movements can be electrified. Based on these numbers, the passenger demand and available seats filters are applied to narrow down the data into plausible high and low scenarios.

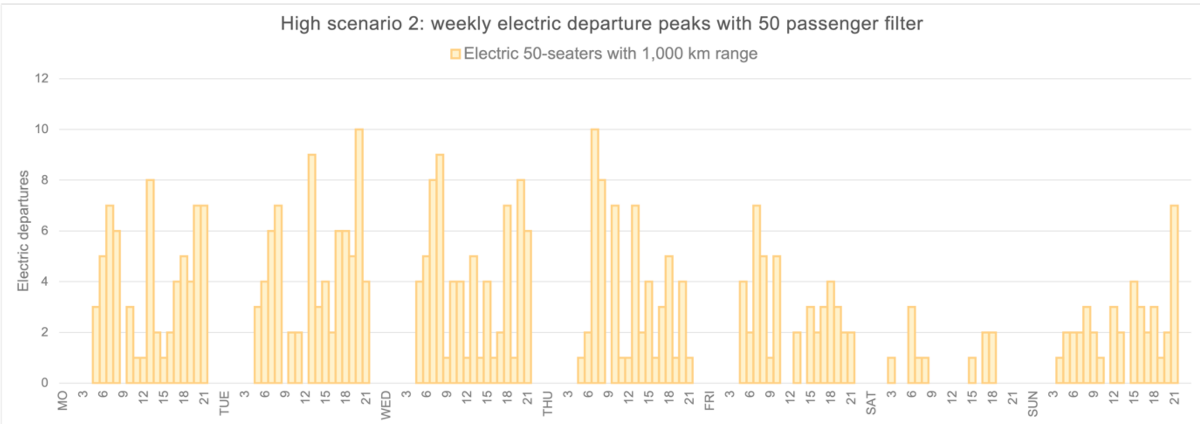
### 5.2.1. High scenario: 50 passenger filter

Applying the 50 passenger filter to the range filter, the number of destinations that can be operated to with electric aircraft from Stockholm Arlanda Airport, decreases from 43 to 40, as shown in table 9. Here, the number of possible electric flights sees a decrease from 1,391 to 364.

| | High scenario: 50 passenger filter |
|---|---|
| Movements [per week] | 364 |
| Peak movements [per hour] | 10 |
| Destinations [per week] | 40 |

*Table 9: High scenario 2 electric movements and destinations*

The same confidentiality reasons as mentioned in the high scenario 1 are applied in this scenario. Therefore, the exact destinations cannot be shared. Nevertheless, an overview of the weekly electric departure peaks of this high scenario can be found in graph 3. This graph illustrates that the peaks mainly occur during the morning and late afternoon, with a maximum peak of 10 electric aircraft departing in the same hour.




*Graph 3: Weekly electric departure peaks high scenario 2*

One important point to notice here, is that the main decrease in destinations and movements can be recognized in the routes connecting Stockholm Arlanda Airport to other hubs. One of the reasons for this, are the triangular flights starting from ARN, connecting through surrounding hubs like Copenhagen or Oslo with aircraft like the Boeing 789. The intention of these flights is not to fill the entire seat capacity of a Boeing 789, but rather to feed the next destination with passengers from ARN.

### 5.2.2. Low scenario: 50 seats filter

Applying the 50-seats filter to the 1,000 km range filter and the seats filter, the number of destinations that can be operated by an electric 50-seater aircraft notably decreases from 40 in the high scenario to 12 in this low scenario, as well a decrease in possible electric flights: from 364 to 80 movements. Figure 5 pictures the destinations of this low scenario, where table 10 elaborates on the movements and ranges of these destinations.

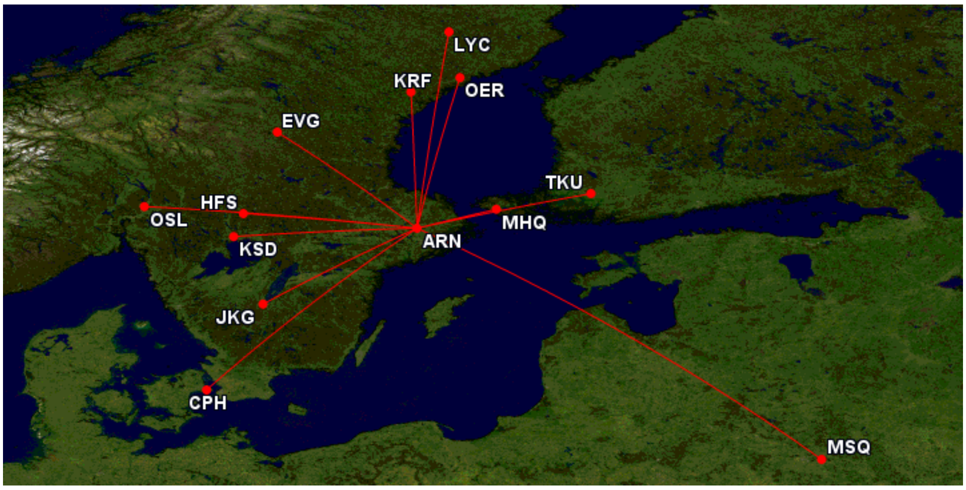
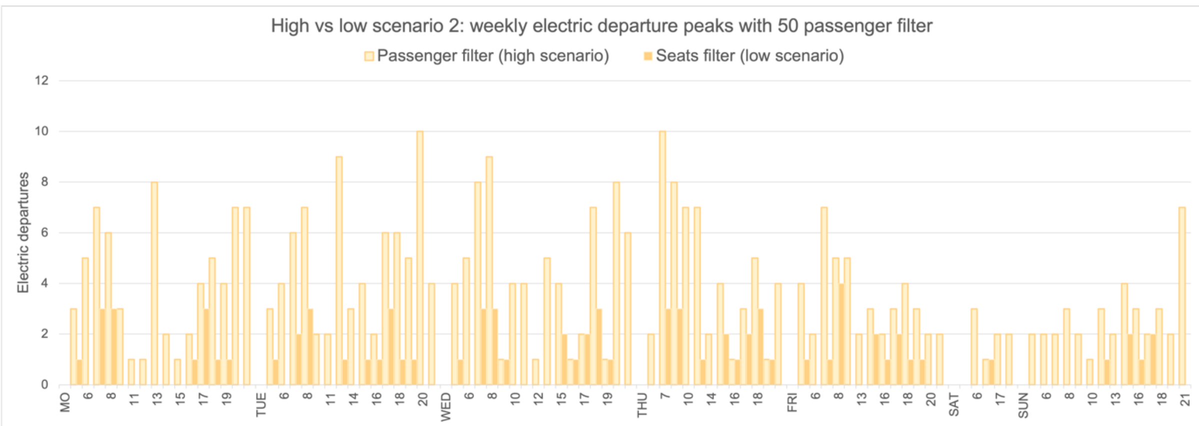



*Figure 5: ARN's electric destinations with 1000 range and 50-seats filter*

| IATA Airport | Airport name | Country | Movements [per week] | Range [km] |
|---|---|---|---|---|
| CPH | Copenhagen Airport | Denmark | 1 | 548 |
| EVG | Härjedalen Sveg Airport | Sweden | 11 | 328 |
| HFS | Hagfors Airport | Sweden | 9 | 247 |
| JKG | Jönköping Airport | Sweden | 11 | 307 |
| KRF | Höga Kusten Airport | Sweden | 4 | 379 |
| KSD | Karlstad Airport | Sweden | 12 | 260 |
| LYC | Lycksele Airport | Sweden | 7 | 547 |
| MHQ | Mariehamn Airport | Finland | 11 | 123 |
| MSQ | Minsk National Airport | Belarus | 3 | 890 |
| OER | Örnsköldsvik Airport | Sweden | 1 | 422 |
| OSL | Oslo Airport | Norway | 1 | 386 |
| TKU | Turku Airport | Finland | 9 | 260 |

*Table 10: Low scenario 2 destinations, movements and range*

Considering the expected departure times of the potential electric flights, graph 4 illustrates the departure peaks at Stockholm Arlanda Airport in the high scenario versus the low scenario. Here, the low scenario shows a peak number of 3 and 4 electric departures per hour. Table 11 summarizes the weekly movement and destination numbers.




*Graph 4: Weekly electric departure peaks high vs low scenario 2*

| | High scenario: 50 passenger filter | Low scenario: 50 seats filter |
|---|---|---|
| Movements [per week] | 364 | 80 |
| Peak movements [per hour] | 10 | 4 |
| Destinations [per week] | 40 | 12 |

*Table 11: High scenario 2 and low scenario 2 electric movements and destinations*

## 5.3. Scenario 3: Electric 100-seater aircraft with 2000 km range

The third and final scenario is a more visionary scenario with 100-seater aircraft and a range of 2,000 km, sketched for the longer term, namely 2050. In this scenario as well as mentioned in scenario 2, the literature review showed a notable optimistic estimation for aircraft development by aircraft manufacturers. The literature in chapter 2 presented a 186-seater aircraft with a range of about 2,000 km. Interviews during this research showed that for this scenario a 186-seater aircraft would be too much of an optimistic view, thus it is more plausible to sketch the scenario with 100-seater aircraft (personal communication April 13, 2021). Here, as well as in section 5.2., the argument about expecting smaller aircraft on longer ranges rather than larger aircraft on shorter ranges, especially in the Nordics due to the geography, is a relevant factor to apply in this scenario sketching.

As the electric aircraft and its batteries are still in development, it is hard to say what the exact developments will be in terms of ranges and passenger capacities. Especially after the first scenario, as sketched in section 5.1., the scenarios and timeframes afterwards become more of a visionary scenario. Even though this scenario might be the most visionary of all, it has still been sketched on a request of Swedavia, to have a, so to say, worst-case scenario for the airport infrastructure consequences. Even though this scenario might be far-fetched, the argument mentioned earlier about the dependency on technology advancement still counts here as well: the scenarios have been based on current technologies and knowledge, but the future, which is still a period of 30 years where a lot can be learned and developed, will tell.

In this final scenario, the 2,000 km range filter will firstly be applied on the flight schedule data, after which the 100 passenger filter (5.3.1.) and the 100 seats filter (5.3.2.) will be applied.

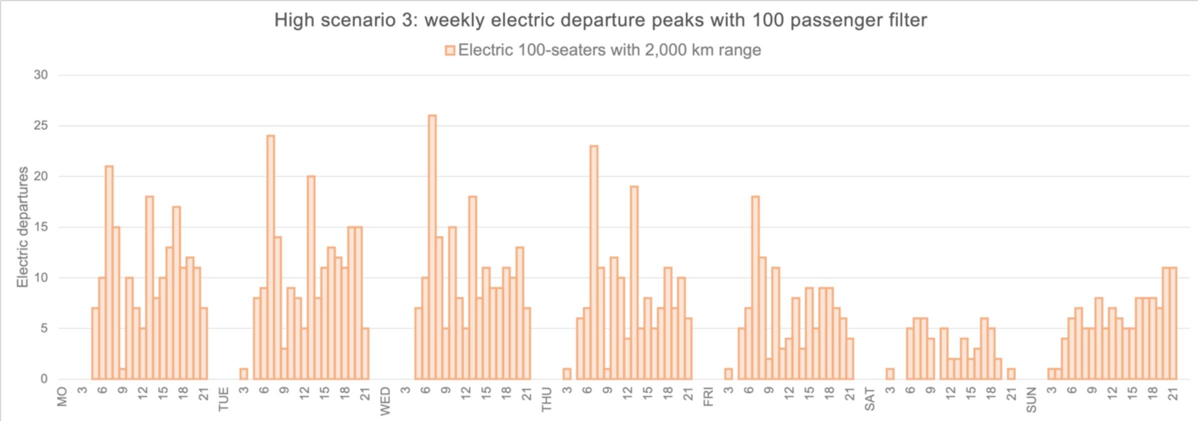
### 5.3.1. High scenario: 100 passenger filter

As table 12 illustrates, the passenger filter, applied to the 2,000 km range filter, shows 1,008 possible electric movements, distributed over 68 destinations.

| | High scenario: 100 passenger filter |
|---|---|
| Movements [per week] | 1,008 |
| Peak movements [per hour] | 26 |
| Destinations [per week] | 68 |

*Table 12: High scenario 3 electric movements and destinations*

Without showing actual destinations, the data on the weekly electric departure peaks at Stockholm Arlanda Airport due to the introduction of electric 100-seaters with 2,000 km range can be given, which are indicated in graph 5. This graph also shows the hourly peaks, which indicate a maximum of 26 electric departures per hour.




*Graph 5: Weekly electric departure peaks high scenario 2*

Applying these same filters as done in section 5.2.1, the corresponding conclusion about the triangle flights can be drawn: this factor needs further in-depth flight schedule data analysis to filter out the aircraft that are part of these triangular routes, or to discuss the possibilities to replace these feeder flights with point-to-point electric feeder flights.

### 5.3.2. Low scenario: 100 seats filter

In addition to the range and the passenger filter, this seats filter creates the third low scenario, as it considers the current aircraft with a seat capacity of 100 passenger seats. With this filter, only the current capacities are considered, not the possible capacities like done in section 5.3.1. This filter identifies 520 possible weekly electric movements, as it shows a reach to 53 current destinations flown from Stockholm Arlanda Airport. Table 13 shows the difference between the third high and low scenario. Figure 6 pictures the destinations that can be reached with this low scenario.

| | High scenario: 100 passenger filter | Low scenario: 100 passenger filter |
|---|---|---|
| Movements [week] | 1,008 | 520 |
| Peak movements [per hour] | 26 | 10 |
| Destinations [week] | 68 | 53 |

*Table 13: High scenario 3 and low scenario 3 electric movements and destinations*

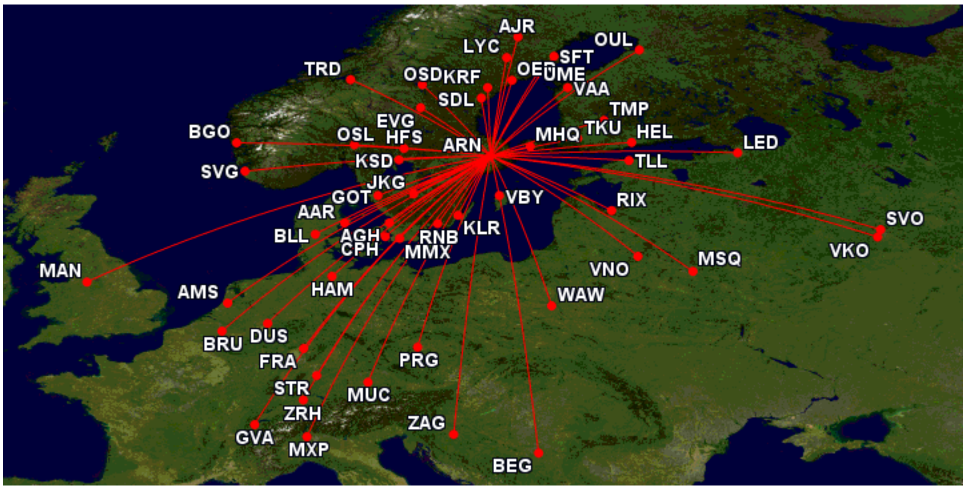
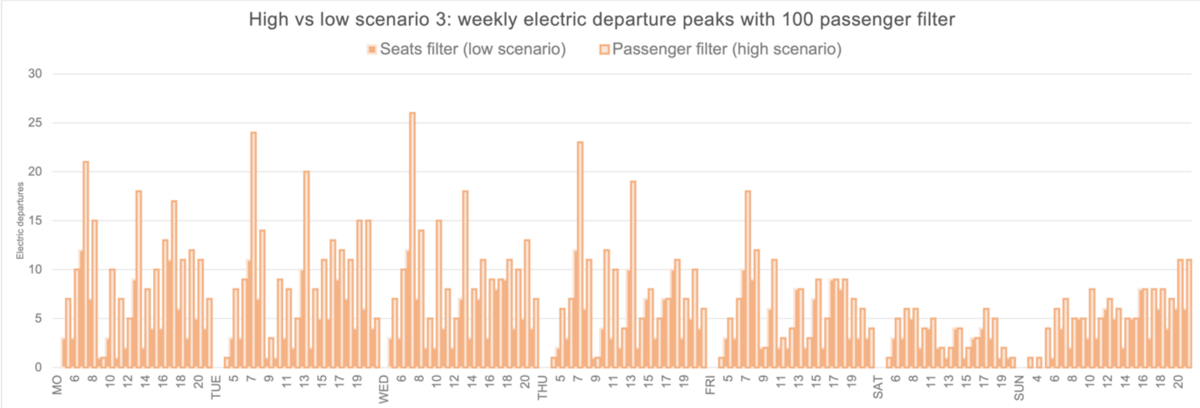



*Figure 6: ARN's electric destinations with 2000 km range and 100-seats filter*

To bring together both scenarios and to differentiate the consequences of each, graph 6 pictures the weekly electric departure peaks of both the high and the low scenario. Here, the low scenario sees a peak of 10 electric aircraft departing per hour.




*Graph 6: Weekly electric departure peaks high vs low scenario 3*

## *5.4. Turnaround times*

For the airlines operating at ARN, as well as any other airport, it is costly to have aircraft on the ground (JT1). Especially after the investment of a new aircraft, like electric aircraft, the airlines will focus on minimizing their time on the ground to maximize their revenues, by keeping the turnaround time to its minimum. The risk with charging electric aircraft is that the charging time may influence the critical path during the turnaround process, increasing the time an aircraft is on the ground.

As the charging times affect the turnaround times, aircraft manufacturers are researching battery charging technologies to bring them to the lowest charging time possible. Currently, fast-charging a 19-seater aircraft is looking feasible to be done within the current turnaround times as 20-40 minutes fast charging is reasonable (more about fast-charging can be found in section 6.1.1.). Even though the technology is already here, batteries are still being developed and are likely to be able to be charged faster (HL1). The charging times will not be a bottleneck, however, it does require investments from Swedavia (personal communication, March 16th 2021)

Turnaround times are not only an external factor influencing the airlines' attractiveness to operate with electric aircraft, but the airport should also consider the turnaround times. In the normal situation, pre-covid, the airport's gate capacity was fully utilized during peak hours (JT1, JN1, AA1). Therefore, the turnaround times of electric aircraft, thus charging times, should be considered as the airport might not be able to facilitate smaller electric aircraft to occupy the stands longer than regular (and larger) aircraft would do (GB1).

Even though the fast-charging technology is developing rapidly and should not cause any problems during the turnaround process, it is interesting for Swedavia to further research possibilities to make slow-charging during the night more attractive. Slow-charging electric aircraft has many benefits related to the airport energy management perspective with its minimum impact on the grid (as further elaborated on in section 5.9.), which may generate a new business model to differentiate the charging prices and make slow-charging less expensive than fast-charging. However, this is a cost-benefit research that is necessary to include in further research as the slow-charging benefits might not weigh up to the cost for the airline to have an aircraft stay overnight at Stockholm Arlanda Airport, causing an airline to choose for the fast-charger anyways.

## 5.5. Airline network development

The data analysis as displayed in section 5.1., 5.2. and 5.3. describes the first steps in the determination of the electrified routes scenarios. When focusing on the number of possible routes in 5-10 years (scenario 1), 10-20 years (scenario 2) and 20-30 years (scenario 3) time, external factors like expected network development of airlines should be taken into consideration to increase the plausibility of these scenarios. New routes are always part of a forecast when planning ahead for such a long time, so several factors should be considered. This thesis research found, based on the field research, conducted interviews, attended conferences and working groups, several arguments for an increase in routes, as well as counter arguments, causing a decrease. Section 5.5.1. elaborates on the arguments for an increase in routes, where section 5.5.2. specifies the reasons for seeing a decrease in routes.

### 5.5.1. Increase in routes at ARN

In addition to the scenario data in the previous sections, two main network developments causing an increase in the number of electric movements can be specified:

- Electric aircraft operators as new market players starting to introduce new routes and operate smaller regional flights (GB1). Those new flights see a leading focus on domestic routes, especially in the Nordic countries due to their geography, which requires aviation connections to the rural parts of the country that are not connected to a hub. Therefore, these areas are expected to be the first to see an increase in domestic flights (JT1, MF1).
- Existing airlines integrating electric aircraft into their fleet mix and substituting (part of) their current passenger flights by electric aircraft. In this case too, current airlines are more likely to start electrifying their domestic routes first, or to see them create new routes as domestic feeder flights. These might be multiple daily flights with smaller electric aircraft during the lower demands, which differentiates their fleet division and increases their connectivity (HL1).

Right now, there is no direct answer to the question whether there will be any added routes, and if so, which routes these will include since it comes down to several factors. It is vital to consider the passengers' motive to travel: whether they travel for business versus leisure purposes, including whether their final destination is Stockholm Arlanda Airport or if they transfer through the airport. In addition to that, connectivity from the destination of departure to ARN is another factor, as well as if the airline's hub focus is on Stockholm Arlanda Airport or another hub (JT1).

Besides those factors, surveys showed Swedavia that, in addition to new domestic routes, the Baltic states and west-Finland would be interesting areas for new electric routes, as these areas are on shorter ranges and included in Stockholm Arlanda Airport's catchment area (JT1).

### 5.5.2. Decrease in routes at ARN

Even though the points mentioned in section 5.5.1. indicate that new routes could be initiated, there are several counterarguments to consider when looking at the perspective of future network development. Firstly, electric aviation might change the way of traveling as it is more likely to operate domestic point-to-point flights, instead of operating following a hub-and-spoke network via ARN, like 95-100% of the current Swedish flights (JT1). Almost all these domestic passengers connect through the hub to another Swedish destination and do not end at Stockholm Arlanda Airport. Once direct flights will be offered between smaller regional airports, it is most likely to see a decrease in demand for (new) flights connecting through ARN (MF1).
The second argument is one related to the current situation, as current business travel sees a huge decrease in demand because almost everybody is working from home and meeting

online due to the Covid-19 challenge. In addition to that, flight shaming can affect the choice of travel for Swedish citizens, causing a decrease in domestic flights.

The sustainability goals of many airlines, as well as the results from interviews and working groups collected in this research, indicate that there exists a willingness to support the movement to a green way of transportation by aviation, however, it is yet unidentified to what extent battery electric aircraft would be part of this adaption. It could be so that the battery electric technologies are not interesting for an airline to invest in, due to the capacities or level of investment cost, which could prevent the regional aviation segment from becoming battery-electric. Developments should be followed closely, but for now, the short-term plans for shorter flights all seem to focus on battery-electric aircraft. After that, time and technology developments will tell.

A conclusion that can be drawn for the airline network developments, is that the increase or decrease in routes depends on the technology development and the interest of existing and new market players to integrate electric fight in their business model. The scenarios sketched in section 5.1.1. on the passenger demand and the capacity as described in 5.1.2. function as a good base to determine the electric routes and how quickly the electric aviation might require change in the airport's infrastructure. Cooperation between Swedavia, the currently serviced airlines, regional airports, and new interested market players is required to determine the potential demand for new electric flights connecting to Stockholm Arlanda Airport. The feasibility to replace or add domestic flights by electric aircraft would depend on the passenger demand on that route, and once the route remains profitable, even with a 19-seater, it could be replaced by an electric aircraft (JT1).

### *5.6. Stockholm Bromma Airport*

Stockholm Bromma Airport (BMA) is a Swedish domestic airport located 40 km south of Stockholm Arlanda Airport. With about 8 km distance between Bromma and the city center of Stockholm, it is a very attractive airport for regional point-to-point flights. However, the closing of Bromma Airport in 2037-2038 is still an ongoing debate in Swedish politics and for Stockholm's long-term planning. Swedavia issued a report stating that it was no longer financially justified to continue operating the airport, on which the government has responded with discussions and statements to actually close down the airport (Personal communication, March 16$^{th}$, 2021).

The closing of Bromma Airport in 2037-2038 would not influence ARN's domestic flight numbers in the first scenario for 2030, but for scenario 2 (2040) and scenario 3 (2050), this discussion is necessary to include. As mentioned before, mainly domestic flights are expected to be replaced first by electric aircraft, and as Bromma Airport functions as the domestic airport in Stockholm, it would mean that ARN expects a significant increase in new domestic flights once Bromma gets closed down, as Swedavia's long-term forecasters assume that 70% of the domestic traffic of Bromma would move to Stockholm Arlanda Airport (personal communication May 12$^{th}$, 2021). This would have a significant consequence for the expected electric movements at ARN, thus the required capacity and infrastructure changes to handle these electric aircraft.

### *5.7. PSO routes*

The route showed in section 5.1.2, Stockholm Arlanda Airport (ARN) – Sveg (EVG), is a destination that is operated as a Public Service Obligation (PSO) route (JT1). PSO routes are established to ensure that suitable scheduled air services are maintained on routes that are crucial for the region's economic growth (European Commission, 2021). As the Swedish government is paying for this route, European and Swedish regulations are applied. These regulations include requirements and conditions for the PSO operators to focus on accessibility based on aircraft range, frequency and seat availability. Research has been done by the Swedish Transport Administration on the possibility of electrifying those PSO routes. One of the outcomes of this research is that there is the intention to turn those routes 'green', but it is not specified yet if that would be through biofuel, hydrogen or electrically, as that is a decision for the airline operating on that route (JN1, MT1).

Cost-wise, PSO routes are interesting to research as possible electrified routes, since they only operate once or twice a week and and the burden of the cost, for example for aircraft waiting on the ground, is included in PSO contract. This could create an interesting business case, since these aircraft can be slow charged during their time on the ground, causing no or hardly any infrastructural problems for the airport (MF1).

### *5.8. Competition air and rail*

A final factor that should be considered when researching new possible routes that could be operated by electric aircraft, is the current demand for the rail network. All the regional airports that are between 0 and 400 km from Stockholm Arlanda Airport, are interesting to look at, also if they are already connected via the high-speed train network. Just like low-cost carriers did in the beginning, electric flight seems to follow the same new market combinations where it starts competing with the bus, and in this case, the train network (GB1, JN1).

There is an existing competition between air and rail in Sweden, partly strengthened by the flight-shaming matter (as mentioned in section 5.1.5) as well as economical and accessibility reasons, which causes many domestic travelers to prefer the train over the flight. The Swedish high-speed trains aim to connect Stockholm to its surrounding regions and the other way around. This service transports passengers with a high speed through the country, competing with the short-haul flights. Currently, the connectivity of the trains to for example the Northern part of Sweden is not optimal, but these high-speed train developments should be considered when looking at the introduction of new routes and its competition in the later scenarios.

However, the current trains connecting to surrounding regions with high passenger capacities like Gothenburg and Oslo (Norway) do not connect to Stockholm Arlanda airport, but to the city center of Stockholm. The only high-speed connection from the city center to Stockholm Arlanda Airport is the Arlanda Express, which is a direct train only operating between Stockholm city center and the airport.

Looking at new flights to feed passengers into Stockholm Arlanda Airport for connecting (international) flights, a difficulty can be recognized due to the expected improvement of the rail network and its speed of transportation around Stockholm. This competitiveness might be a factor to prevent setting up new feeder routes from surrounding regional airports to ARN. However, timewise, a feeder route would be more attractive by flight as the security checks are done at a small regional airport instead of a large airport, which would be the case when connecting by train. In addition to a time advantage, passengers might be attracted to electric aviation again as is the most sustainable option with its zero-emissions and no impact on land, compared to the rail options (Broekema, 2020).

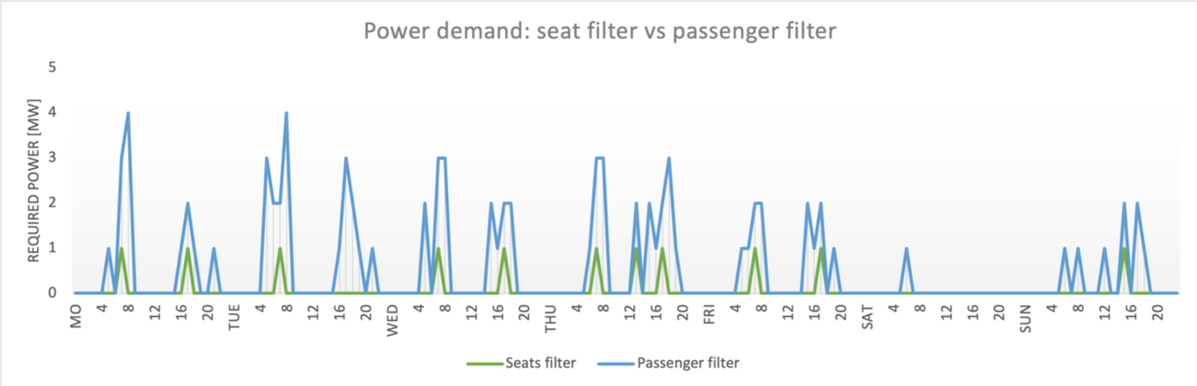
This competitiveness is an interesting factor to consider when researching new routes, however, this thesis research does not include further research in which routes would be plausible to be replaced by electric flight. Some questions that have been found during this research and still require an answer before managing this competitiveness are the following:

- Can electric aircraft reduce costs and thus become more attractive on routes that are also connected through the rail network?
- Which former air routes have been replaced by train, and could it be worth researching and introducing electric flights on?

- Which regions are currently connected by rail and road and which regions are not? Where could new routes be introduced, and is that within the limitations of the expected electric aircraft range?

### 5.9. Electricity needs

Considering section 5.4.'s data on the required 1 MW per 19-seater, a rough calculation can be done for the power demand for electric aircraft at Stockholm Arlanda Airport during the turn-around process, assuming that the battery of the aircraft will be fully charged. Applying the seat- and passenger filter for graph 7, the following peaks occur during a weekly operation:




*Graph 7: Electricity needs [MW]*

With a maximum daily peak load capacity of 20-22MW at Stockholm Arlanda Airport, 1 MW extra demand per hour should be no problem (HP1). In the low scenario, thus the seats filter, these peaks do not override the 1MW demand per hour, so this should not create a problem for the electricity network (HP1). However, the passenger filter's peaks are significantly higher, with a maximum peak of 4MW per hour. For these peaks, new solutions need to be introduced at the airport to cover this demand.

The sections 5.2 and 5.3 illustrate a demand increase for electric aircraft when the seat capacity and the possible range increases. With a peak of 4 electric aircraft per hour in the low scenario of scenario 2 and 12 aircraft per hour in the third low scenario, it exceeds the demand peaks of the high scenario in scenario 1. Therefore, it is crucial for the airport to start planning ahead and discover the various options to expand the electricity capacity. One important factor for the electricity needs in scenario 2 and 3, is that the aircraft seats AND aircraft ranges increase. When both the size of the aircraft AND the operated distance increases (both requiring bigger batteries), and considering the same battery technology and the current aerodynamic efficiency, eventually several megawatts power demand will be reached per aircraft. However, this all depends on the future technology advancements, and it seems probable that batteries would get better in terms of specific energy which could lower the weight of the aircraft, assuming that the same on-board energy capacity will be maintained (HA1). Since further research is needed on the specific power demands for scenario 2 and 3, this thesis will not go in further detail in the electricity needs applied to these scenarios.

With the power demand increase in mind, several options can be considered to address the electricity requirements, while maintaining the regular airport electricity needs at the current green status (HP1, PO1):

- Enhancing the electricity grid.
  The airport is dependent on the Stockholm area grid, which currently faces capacity challenges. Surveys held by Swedavia energy shows that expansion until an extra demand of 10MW is possible, but after that, new lines and cables need to be built. This could take 10-15 years, turning the electricity grid enhancement into a long-term vision (HP1).

- Battery storage.
  When the electricity grid cannot be enhanced, energy storage is required. This storage would increase cost, but also capacity (HP1). Energy storage through batteries is typically used for a 24-hour horizon to store excess generation, for example generated by solar PVs (see the third point). Also, these batteries can function as a storage for electricity generated during low demands, such as during the night. This way, the airport has a fully charged battery (or batteries) ready to cover the morning peak demand (as shown in graph 7) without the need for any increase of grid power (PO1). Electricity storage through batteries sees two solutions:
  - One large, central, battery unit: one battery results generally in a larger power capacity and output, which means that when the aircraft is being supercharged, it is probably easier to do that with a large central battery than a smaller one. Also, one battery is easier to monitor instead of several smaller ones. Nowadays, there are management systems that measure the temperatures, currents and monitor the cells' operation, so the technique is available (PO1).
  - Multiple smaller batteries spread over the platforms: multiple batteries are more attractive to choose when looking from an operational perspective, since the breakdown of one large battery has more impact than one smaller battery because the other batteries can still serve as back-up. Technically speaking, smaller batteries are more efficient in terms of delivering 1MW with a capacity of 1MW instead of delivering 1 MW with a capacity of 10MW with a larger battery (PO1).

  In the end, the airport should plan the (fast-) charging needs extensively according to the turnaround times and the airline's needs, to determine what kind of battery electricity storage and amount of power is needed (PO1).
- Solar PV (photovoltaic) panels.
  Solar panels could support the electricity need of the airport in terms of own production. It is typically used to support the grid and in combination with battery electricity storage, to store excess generation by solar PV panels. Energy is stored during the most PV output which can be used later to cover the peak load (PO1). Even though several Nordic airports, like Copenhagen and Kalmar airport (MF1, MP1), already implemented these Solar PVs, Swedish regulations prevented Stockholm Arlanda Airport from locating Solar PVs near the airport. Regulations that should be considered in this light are EMC (Electro Magnetic Current) regulations on the disturbance for the radio communication systems and the regulations on solar reflections, causing disturbance for the pilots' vision in the surrounding area of the airport. Further research is required on this, and currently RISE (Research Institute of Sweden) and Kalmar airport are exploring these areas and reporting on it (PO1, HP1, MF1).
- Vehicle to Grid (V2G): Vehicle to grid supports the grid by transferring excess power from the electric car to the grid. Take for example 10 Teslas, which might deliver about 1MW, if the technology is there (HP1). The downside of this option is that it is highly uncertain how many vehicles are available, as well as how many owners are willing to participate (PO1). Further research is needed for the willingness, the power generation per car and the technology options. Interviews done during this research showed that Polestar and Nissan are busy developing this V2G technology (MP1, MF1).

Next to the solutions to cover the peak demand, another vital solution for the airport is to 'shave the peaks' (OL1, PO1). This solution includes all three options as described above. Shaving means that energy is imported from the grid, in combination with using the (f.i. the solar PV) energy that is stored in the storage capacity. This combination could be a great opportunity to lower the required grid demand, which is an important factor given the great challenges the electricity grid is facing nowadays already. An increasing demand not only from the electric aircraft, but also from households, transportation and the airport's facilities, MRO, and ground equipment. Import of peak powers at the same time by every sector can cause electricity outages (PO1).

A final solution for the peak demands, is to decrease the required power at the same time. From this energy management perspective, it is prevented that all electric aircraft are charging at full power at the same time. Here, profound planning is required by the airport, to map out the time in which the aircraft needs to be charged according to turnaround times of the aircraft shown by the arrival and departure times, and what the needed power is for the charging process according to the aircraft's next destination shown by the flight data. Fortunately, there is great access to the flight path that can be used for the aircraft charging planning to reduce the stress on the grid (PO1).

Looking ahead, it will be highly probable that a mix of all options as mentioned above will be chosen. The first step would be building battery packs (electricity storage) to cover the first peaks, and a next step would be to install solar panels to generate energy in high production hours (ES1). Further research is needed to determine the exact moment on which network enhancement is needed. This research should start in time because, as mentioned earlier, the enhancement of the network takes 10-15 years. In addition to this recommendation, the following questions - outside this thesis research scope – came up which can fuel further analysis:

- Who will take the responsibility as electricity facilitator at the airport? Will this be the airport itself, the current fuel distributor, the electricity provider, or another party?
- How could the current problems with the Solar PV regulations be solved to introduce electricity production from Solar PVs?
- What are the investment costs of charging infrastructure and battery storage and are these feasible investments for the airport?
- What are the handling safety issues of battery storages?
- Can electricity storage be located on airside?

### *5.10. Sensitivity analysis and scenario discussion*

The scenarios are dependent on a lot of factors. The first flight schedule-based outcomes show that the range filter alone is not reliable enough to demonstrate plausible scenarios. In addition to that, the data is very sensitive in terms of an applied seat filter or passenger filter, like table 14 illustrates.

| | High scenarios (passenger demand) | | | Low scenarios (available seats) | | |
|---|---|---|---|---|---|---|
| *Scenario* | **1** | **2** | **3** | **1** | **2** | **3** |
| Movements DEP [week] | 86 | 364 | 1,008 | 11 | 80 | 520 |
| Peak DEP [hour] | 4 | 10 | 26 | 1 | 4 | 10 |

*Table 14: Hourly and weekly movements scenario 1, 2 and 3*

On top of the data analysis, the external factors shown in table 15 influence the number of expected electric aircraft at Stockholm Arlanda Airport.

| Factors increasing expected electric aircraft | Factors decreasing expected electric aircraft |
|---|---|
| Airlines substitute aircraft operating domestic flights by electric aircraft | Domestic point-to-point traffic, instead of current ARN hub connections |
| Airlines introducing new domestic routes with electric aircraft connecting to ARN | Lower passenger demand due to flight shaming |
| Electric aircraft operators enter the market and start new domestic routes | Less short-haul (business) flights due to covid-19 pandemic |
| The closing of Bromma airport: adding (possible electric) domestic routes to ARN | Longer turnaround time due to charging time |
| Operational attractiveness for electrifying the PSO routes | PSO governmental priorities |
| Electric air travel is a more sustainable option than train travel | (Regional) train competitiveness |
| | Slow technology developments decreasing the attractiveness for battery-electric aircraft |

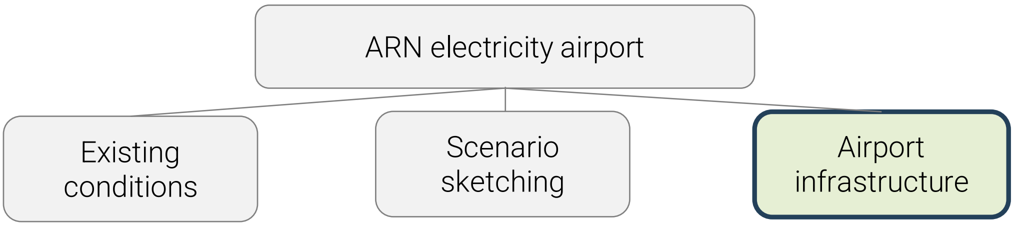
*Table 15: External factors increasing and decreasing possible electric routes at ARN*

The results from the scenarios sketched in section 5.1., 5.2. and 5.3. indicate that, due to scenario 2 and 3 being dependent on scenario 1, the first scenario is the most important to invest time and research in. Looking at the first high and low scenario, the highest hourly power demand peak Stockholm Arlanda Airport would see is between 1 and 4 MW. As section 5.9. argued, the airport would be able to handle a power demand of 1MW per hour, so in order to support the introduction of electric flight, the electricity peaks need to be shaved by grid enhancement, battery storages, solar PV production and vehicle to grid solutions. In addition, the electric aircraft power demand management is a cruciality to consider to not over-stress the grid during the charging process.

As the key factors and external forces influence the outcome of the scenarios greatly, the most vital influencing uncertainty are the technology developments of the batteries and the aircraft. Scenario 1 shows most feasibility due to the extensive research that is done today by Heart Aerospace, but greatly depends on the external factors. The scenarios afterwards depend on the outcomes of the first scenario and are only plausible if the battery and aircraft technologies continue developing. Without the actual technology, the electric aviation losses its attractiveness for airlines and aircraft operators to integrate electric aircraft in their fleet mix.

Concluding, it is essential to actively perform further research on the mentioned factors together with the involved airlines (new routes or replacement of routes), new market players (introduction of new routes), government (PSO routes), aircraft manufacturers (decrease fast charging times and research safety aspects), energy providers and determine the impact of the air and rail competition. Once these factors have been assessed together with the actual developments in this segment, they can be added to the first sketched seat scenario.

# 6. Results: Space requirements




Electric aircraft are location-bound as they are most likely to operate point-to-point traffic between existing regional airports (GB1, HL1, JN1, JT1, MF1). A comparison that is often made, is the one between the electric automotive industry and the electric aviation industry when it comes to technology. However, when discussing handling requirements, the aircraft is dependent on the airport infrastructure, where the automotive industry sees a larger flexibility with charging stations. With the introduction of electric aircraft, the airport is directly connected thus required to adjust accordingly to the needs of the electric aircraft and research the consequences it would bring to the layout of the airport's airfield, in this case, Stockholm Arlanda Airport's airfield.

The current airport infrastructure is designed to handle regular jet-fuel aircraft, including all required facilities to turn these aircraft around as fast as possible. With the introduction of electric aircraft, thus a new technology, the airport is required to research the needs of these aircraft and what consequences that would bring to the current infrastructure at Stockholm Arlanda Airport.

The existing conditions in chapter 4 and the scenarios sketched in chapter 5 indicate the size of the introduction of electric aircraft at Stockholm Arlanda Airport. This chapter will define the required technical-, safety- and capacity-related factors for airports to adjust their infrastructure capacities and meet with the demands for electric aircraft. Since chapter 5 illustrated that the scenarios sketched are reliant, thus scenario 2 and 3 can only be known once scenario 1 has been confirmed, this chapter will focus on the required infrastructure adjustments to cope with the first introduction of electric aircraft. The new situation will be sketched in comparison to the current situation, but there will be no detailed elaboration on the growth of the new situation towards the visionary scenarios 2 (2040) and 3 (2050).

Section 6.1. will elaborate on the needed infrastructure, thus the required facilities, standardization, and responsibility. The safety and space requirements related to the airport infrastructure and electric aircraft handling will be discussed in section 6.2., followed by 6.3. on the placement of the electric aircraft at Stockholm Arlanda Airport.

## *6.1. Needed infrastructure*

The needed infrastructure is, as shortly mentioned in this chapter introduction, a new terrain for the airport and its ecosystem. As discussed in section 5.9., the energy needs of the airport will change with the introduction of electric aircraft which will bring new challenges, thus require new solutions. There is a big number of research projects going on to develop electric aircraft, however, the airport requires to change with and needs to be aware of the changes this introduction might require.

### 6.1.1. Charging facilities

Starting with the charging facilities, which is the base of the electric aircraft and its ability to get back into the air and transport passengers between destinations, which is what it was designed for. Chapter 5.4. defined the importance of turnaround times for airlines, which is a vital factor for required charging facilities. Without a maximum time to be turned around in, there is no need to develop a fast charger to stick within a set time frame. However, for airlines it is costly to have their aircraft on the ground, thus a turnaround time is relevant in this equation. Therefore, the first required infrastructure, or facility, that comes with an electric aircraft, is the fast charger.

The area the electric aircraft will be handled at, which will be elaborated on further in section 6.3., requires all facilities for the aircraft, from energy storage to comply with the needed power demand, to the right connectors that fit the aircraft connector point. The turnaround times show the need for a fast-charger, but as mentioned in section 5.9. on the electricity needs, there should be a possibility to adapt the speed of charging, thus the charging power, according to the time the aircraft takes to turn around. This way, slow-charging as well as for example charging on medium power and fast-charging should become available. To lower the investment cost and prevent the investment in several chargers for the different modes, the airport should, together with aircraft manufacturers, research the possibilities to charge different power demands through the same charger.

Safety challenges arise if chargers are required to fast-charge a 19-seater aircraft with 400 km range with a power demand of 1 MegaWatt, if not more once the battery capacity increases. Aircraft manufacturers are researching multiple charging points to ensure the safety during charging, as one charging point might generate too much heat due to the power loads. One charging point, thus one charging cable, would also cause safety issues regarding the handling staff as the cable would become too heavy to work with, thus would require for example robotic solutions (personal communication March 16th, 2021). Assuming that these multiple charging points will be integrated in the charging process, it would require more space and actions proceeded by the personnel on the ground. Stockholm Arlanda Airport should monitor these developments closely, to be informed adequately about the number of connector points and the required space for the charger cables, as well as the required connections to the grid, or battery storage facilities.

Through the conducted interviews and attended conferences and working groups as part of this thesis, it became clear that the responsibility of creating fitting charging infrastructure does not belong to the airport's tasks, but with the aircraft manufacturer and the certification process of the aircraft (personal communication, April 19th, 2021). Therefore, this sub-chapter does not elaborate further on the specific chargers that are required. More information on the standardization can be found in section 6.1.2., on the standardization processes.

Next to the charging infrastructure, there are several facilities needed as part of the electric aircraft charging process, amongst others:

- Electricity storage
  To support the grid when there is a large (peak) demand for power, storage facilities are an option to work with. As can be found in section 5.9., this research shows two possibilities: one large, central storage, or several smaller units located near the chargers, thus near the aircraft stands. These options each have different consequences, as the larger storage unit takes in more space in one location but can be located in a less dense and less valuable area. Smaller storage units, however, could be used as electricity storage per charging facility, which means that it would take in space at or near the platform, which is a very strict area when it comes to regulations on the occupation of space. As also recommended in section 5.9., the airport should make extensive calculations on the required power, and what kind of storage facility would be the best corresponding option. As this topic is still very new on aviation grounds, research is required on the possibility to place the storages units on airside, or if it is not allowed due to safety regulations.
- Cooling equipment.
  Cooling facilities are needed to continue fast charging without reducing the lifetime of the battery (personal communication, April 19th 2021) (OL1). The size and safety of

these facilities are still unknow but are essential in this equation to consider and to perform further research on.

- Monitoring or management systems.
  These systems are required, if not already part of the charging infrastructure and electricity storage, to keep a safe operation. Some of these management systems measure the temperatures and currents, and monitor the cells' operation (PO1).

More technical solutions to complete the entire connection between the electricity grid and the aircraft are required, but since this does not directly influence the main research question, these technicalities will be left out of scope. Nevertheless, the energy department of the airport should be closely involved as it can map-out the required steps to connect the aircraft to the main power points.

#### 6.1.2. Standardization and certification

Standardization is the foremost important factor to consider when working on new developments. There are currently many electric aircraft developers, but with shattered technologies and infrastructure, the aviation segment misses the one thing they stand for: connecting airports. Missing this synchronicity results in limiting electric aircraft to airports that apply the infrastructure that specific aircraft type requires. Therefore, standardization of charging infrastructure is needed, to allow electric aircraft to connect to as many airports as possible.

The current standardization bodies working on charging station infrastructure, is the working group 112 (WG112) at EUROCAE. Even though this working group is focused on eVTOL (electric Vertical Take-Off and Landing aircraft) infrastructure, it is an important first step towards regional aircraft as it complies with probably the same safety aspects and power requirements as expected for regional aircraft (personal communication April 19th, 2021). A working group for regional or commuter aircraft is not set-up yet, since the first step in electrified aviation are the eVTOLs and small aircraft like the Pipistrel Virus SW 121.

The certification of the Virus SW 121 together with the certification of various eVTOLs has shown that the charger certification and the aircraft certification is a joint process (personal communication April 19th, 2021). These two aircraft types function as a base for the certification of regional or commuter aircraft, as they comply with the same safety aspects and power requirements (personal communication April 19th, 2021). The means of compliance developed for Pipistrel and eVTOLs are likely to be tailored and applied for regional aircraft. The highest level of means of compliance is now on the eVTOL level, any level higher than that has not been developed yet (personal communication April 19th, 2021). Not only the aviation industry is working on regulation development for the charging of larger vehicles. The heavy truck industry is already working with larger trucks and comparable charging systems and power demands. For example, NREL, National Renewable Energy Laboratory, is working with other U.S. based labs to develop a megawatt-scale charging system for medium- and heavy-duty electric vehicles, please refer to appendix II for a situation sketch (Meintz, 2021). CharIN is working on developing MCS (MegaWatt Charging System) for the heavy truck industry, with the intention for it to support the development of charging systems and its regulations for the electric aviation industry (CharIN, 2021).

SAE international (SAE StandardsWorks) has a current working group, E-40 Electrified Propulsion Committiee (SAE, 2021), working amongst others on the standardization of the charging connector, which is the connector between the charging cable and the aircraft. Their research is based on the available charging connectors in the current market, from which they select the most ideal connector for aviation, in this case General Aviation (personal communication April 19th, 2021).

Where this thesis started with an understanding that the priority of electric aviation developments lies with the standardization and certification of the chargers and connectors (HL1), the final focus group discussion argued differently. The NEA working group, together with Heart Aerospace, is finding first arguments that the connector standardization might not be such a big problem as assumed in the beginning (MF1). The reason for this is that research seems to show that it is not that difficult to change the charger or connector later in the process. However, this does not imply that synchronicity is not the top priority. It implies that the bottleneck of electric aircraft development does not lie with the charger standardization, as it seems relatively easy to change the connector both at the aircraft and the cable itself (personal communication May 4th, 2021).

Not only for the aircraft operator it is crucial to have one standard. At the airport, standardization is required for having one operator handling the charging infrastructure and avoid fragmentation or differentiation in the infrastructure. A consequence of having several operators, could be that several chargers are located at one platform, for which the airport does not have the space. Especially in the beginning, the airport, in this case airport operator Swedavia, should supply the facilities to remain synchronicity and flexibility (HP1). This synchronicity allows flexibility for the airport infrastructure depending on the demand fluctuations of electric aircraft. The pricing or financing of this new infrastructure will also be a subject of discussion between the airport and its stakeholders and needs to be further addressed when more information is available on charging equipment and charging needs (JN1).

As can be concluded from these standardization developments, it is clear that there is a lot of work going on and from all perspectives, stakeholders are working together. Also, the NEA working group, as mentioned in section 4.2.1., aims to create the Nordic standard for aviation, in order to apply it on a global level as well. Members of NEA are working closely together with EASA to support the development of these standards. In order to commit to the electric aims that have been set in the Nordics, those standards are needed (MF1).

### *6.2. Safety and space requirements*

Adopting new technologies in an existing airport environment requires operational assessments to coordinate with the current Jet A-1 powered operations with equal safety levels. The safety and space requirements for electric aircraft will start with current airport management regulations (personal communication April 19th, 2021). The requirements found during this thesis research are the following:

- Hazard area around the electric aircraft while charging.
  The charging process of an electric aircraft brings new safety concern, as large amounts of electricity are transported from the grid (or storage facilities) to the aircraft. Especially the connecting points between the aircraft and the charging cable requires safety procedures, as it is being handled by humans, in an area with passengers and other flammable equipment around. The hazard area should maintain safety and venting possibilities if there is a fire, smoke, or high-temperature corrosive gases (personal communication April 19th, 2021). The concern here is whether the hazard area is so large, that the electric aircraft cannot be handled at the terminal next to regular jet-fueled aircraft. If the charging equipment demonstrated to be safe without any influence on the area around the aircraft that is being charged, there is no problem to place these electric aircraft next to regular aircraft (personal communication April 19th, 2021). The working group for eVTOLS, like WG112 as mentioned before, is looking into hazard areas during the charging process for aircraft (in this case eVTOL) on ground. The working group is not yet focusing on commuter aircraft, but as indicated in 6.1., these means of compliance will function as a base for commuter aircraft as well, as it is working with the same power amounts on the ground (personal communication April 19th, 2021).

- Firefighting capabilities.
  The airport fire brigade is trained according to the current safety risks of traditional kerosine aircraft. With this new technology, the brigade needs to be trained accordingly, for example to be able to handle battery ignition or other risks near an electric aircraft. Not only specialized equipment should be put in place, it is also vital to train the fire fighters on the possible risks and how to handle them.
- Staff training.
  Next to the training of fire fighters, it is critical to begin training people on the development of aircraft as well as how to handle such aircraft including learning about the risks. It is vital to begin developing skilled workforce since new and undiscovered areas are introduced, in terms of passenger behavior, new network advancements, technology or aircraft development and airport infrastructure design (GB1).

As every stakeholder benefits from a sustainable way of transportation in a safe way, it is of every stakeholders' interest to develop safety standards as quick as possible. For example, airlines might want to help out solving the safety issues and lobby with the aircraft manufacturers to make the aircraft safe, as a safe operation is their priority. Secondly, airlines require the shortest travel and transfer time for their passengers and increase connectivity, so they might lobby with airports too, for the safest and quickest policies, as well as the supporting ground handling at many airports (JT1).

The safety concerns as mentioned above are the parts that arose during the research. However, there are still questions left unanswered, and some of them that have not been elaborated on in this sub-chapter, but still need in-depth research, are the following:

- Can an electric aircraft be handled (thus charged) next to a regular aircraft while being fueled?
- Can passengers board an electric aircraft while being charged?

Planning and cooperation with aircraft operators should start today to prevent patchwork approaches and to exchange knowledge and information among stakeholders. The lack of uniformity in the aviation industry is a safety concern and a risk that cannot be overestimated (personal communication February 16th, 2021).

### 6.3. Electric aircraft placement

New technologies question the standardized processes at the airport. It is no guarantee that the aircraft and its turnaround processes are safe enough to be handled at the gate, thus might require a different placing option at the airport. This section will acknowledge the placement challenges that come with the introduction of electric aircraft at the airport, followed by the implementation of these priorities at Stockholm Arlanda Airport's current and future airfield map.

The different placement options should be considered, as they are dependent on the safety constraints (section 6.2.) and include large pros and cons. Safety constraints should be considered first, however, the logistic- and investment-related aspects cannot be overthrown. Without any operational considerations on the gate connectivity, transfer timing and passenger comfort as consequence of the aircraft placement at the airport, it might reduce the attractiveness and feasibility for airlines to operate with electric aircraft, thus reducing the feasibility for the airport to invest in this new development.

Based on these considerations, three main issues have been outlined below, followed by the implementation of these points at Stockholm Arlanda Airport's current and future airfield map.

- Safety considerations
  The first and foremost consideration is the safety. As section 6.2. gives an in-depth analysis on the safety aspects, this point will conclude with the statement that unless electric aircraft charging (including required infrastructure) has been proven safe, it cannot be handled at the terminal, thus needs to be handled at a remote area at the airport.
- Building feasibility (investment cost)
  Stockholm Arlanda Airport is built on a location with rural difficulties, like height differences and slopes in the airfield of the airport (AA1). During the discussions with Swedavia master planning, several options for the placement of electric aircraft have been left out of scope, due to these building limitations, thus high investment cost. Another point that should be considered when looking into the building feasibility, is the existing areas that could function as handling area for the electric aircraft. If it is not necessary to build new infrastructural foundations, and existing areas can be used, this would be preferrable to choose.
  One point to consider for the airport is a policy consideration: will the number of stands required all be transformed to electric aircraft stands only, or will the stands function for any type of aircraft, whether it is a traditional jet-fuel aircraft or an electric aircraft (GB1).
  Lastly, Swedavia should consider the stand availability and if there is capacity for an electric aircraft to require a longer turnaround time than regular aircraft do now. Remote stands are limited at Stockholm Arlanda Airport (AA1) and gate capacities are as good as full during the peak hours (in a pre-covid situation).
- Passenger transfer
  If the electric flights contain a lot of connecting passengers, and airlines and airports want to move them within the minimum connecting time (MCT), the different options on placement of the aircraft should be considered. If the electric aircraft are not placed close to the airport, thus the connecting aircraft, due to safety and capacity considerations, it requires the passengers (both transfer and exiting) to be transported from the remotely located aircraft to the terminal, posing various issues in terms of minimum connecting times and passenger comfort. From an airline perspective, especially the hub-and-spoke airlines, a longer minimum connecting time due to the remotely placed aircraft could lengthen the transfers to connecting flights within their network. In addition to that, it would require extra cost and logistical challenges concerning amongst others the air traffic controllers, to transport the passengers by bus from the aircraft to the terminal (GB1).
  However, if it turns out that, due to safety concerns of the hazard area around the electric aircraft (section 6.2.), the aircraft cannot be handled at the terminal, the only option would be to place the aircraft remotely.

In addition to the main challenges mentioned above, the master planning perspective indicated several points that should be considered before the placement of the aircraft can be decided (personal communication May 11th 2021):

- Electric aircraft are expected to be categorized according to ICAO Aerodrome Reference Codes as Code C aircraft in terms of wingspan (JN1, AA1). However, the height sizing of the aircraft is expected to be smaller than the regular Code C aircraft. Therefore, it is preferable to have electric aircraft stand at remote stands instead at stands connected with an airbridge. There is one terminal at Stockholm Arlanda Airport having remote code C stands, which is Terminal 3.
- If possible, it is preferable to have the electric aircraft located near the domestic terminals, which are Terminal 3 and 4.

Fortunately, the airport has a terminal with 4 Code C stands (and 4 stands for small aircraft), which are all remotely located at one side of the terminal, thus not connected by air bridge to the terminal, and do not require busing between the aircraft and the terminal. This terminal,

terminal 3, is not designed for Code C aircraft in terms of passenger numbers, but for smaller aircraft. Again, fortunately, the expected electric aircraft will start with a capacity of 19 seats (AA1).
From an energy management perspective, the electric aircraft will be charged from cables that are underground connected to the main power units. It is most preferable to have the electric aircraft and its chargers as close to the main power points as possible to decrease the energy losses (as those losses decrease the closer you are to the main points) and to have the lowest investment cost due to new power cable connections. There are two main electricity points at the airport: one on the north side of the existing terminals and one near the cargo area in the south (HP1, JN1).

Applying the energy and master planning considerations (JN1, HP1, AA1) on the current lay-out of Stockholm Arlanda Airport, the short-term results in terms of pros and cons have been listed in table 16 and 17, followed by a visual presentation of the airport in figure 7. It is vital to mention that option one is only possible if safety considerations allow electric aircraft to be handled, thus charged at the terminal stands.

**Option 1: Terminal 3**

| + | - |
|---|---|
| Located at the terminal: passenger comfort and transfer time benefit<br>Remote stands at the terminal: no airbridges<br>Close to train station for train transfers<br>Close to main power point | Uncertain if electric aircraft can be handled at the terminal (safety perspective)<br>Capacity challenge: pre-covid there was no space left |

*Table 16: Short-term electric aircraft placement option 1*

**Option 2: Northern remote stands**

| + | - |
|---|---|
| Good short-term option: groundwork/ foundation is already there<br>Remote stands<br>Close to main power point | Parking place for regular aircraft, uncertain if there is enough space for electric aircraft<br>Located at the international side of the airport, with a long connection to the domestic terminal. |

*Table 17: Short-term electric aircraft placement option 2*

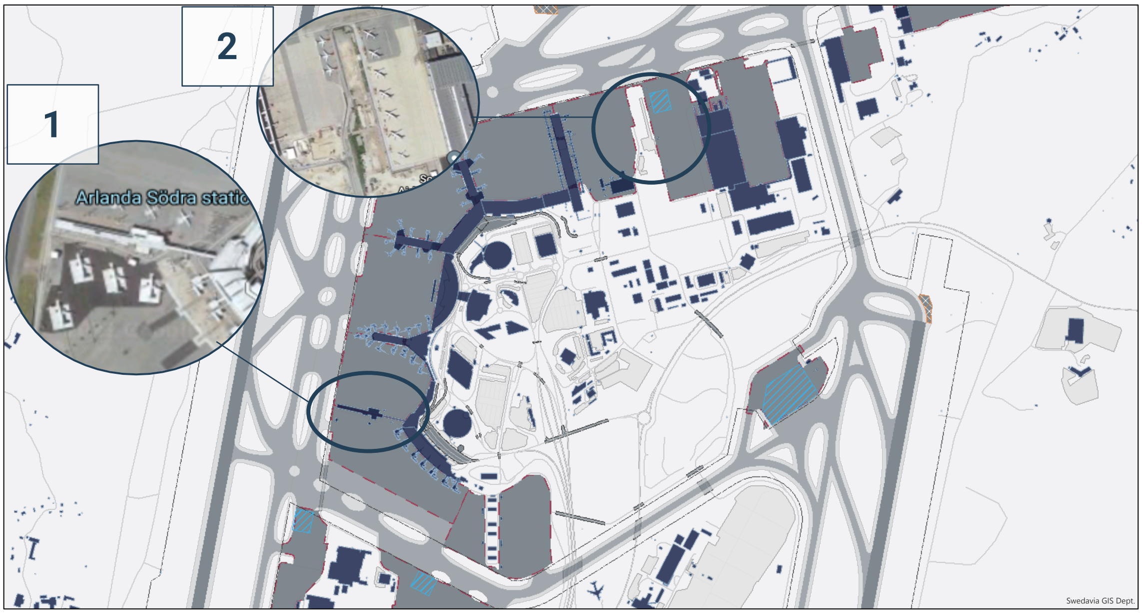



*Figure 7: Short-term optional electric aircraft placements at Stockholm Arlanda Airport*

For the long-term option, the short-term options are still valid (assuming that the first option, with Terminal 3, can handle the optional capacity increase), and one option can be added: Option 3 (table 18). Swedavia has been planning several expansion steps until 2070, to be able to handle 70 million passengers per year. Figure 8 shows the three options in the 2070 master plan for Stockholm Arlanda Airport.

1. Option 1: Terminal 3
2. Option 2: Northern remote stands
3. Option 3: Cargo area

**Option 3: Cargo area**

| + | - |
|---|---|
| Good long-term option if cargo area will be moved<br>Close to main power point + cables are prepared for new connection | Current cargo area, if this area is not moved, it brings many logistical challenges<br>Current capacity is limited, especially since covid pandemic<br>Buses will be crossing one taxiway (maybe 2 in the future), concerning ATC operations |

*Table 18: Long-term electric aircraft placement option 3*

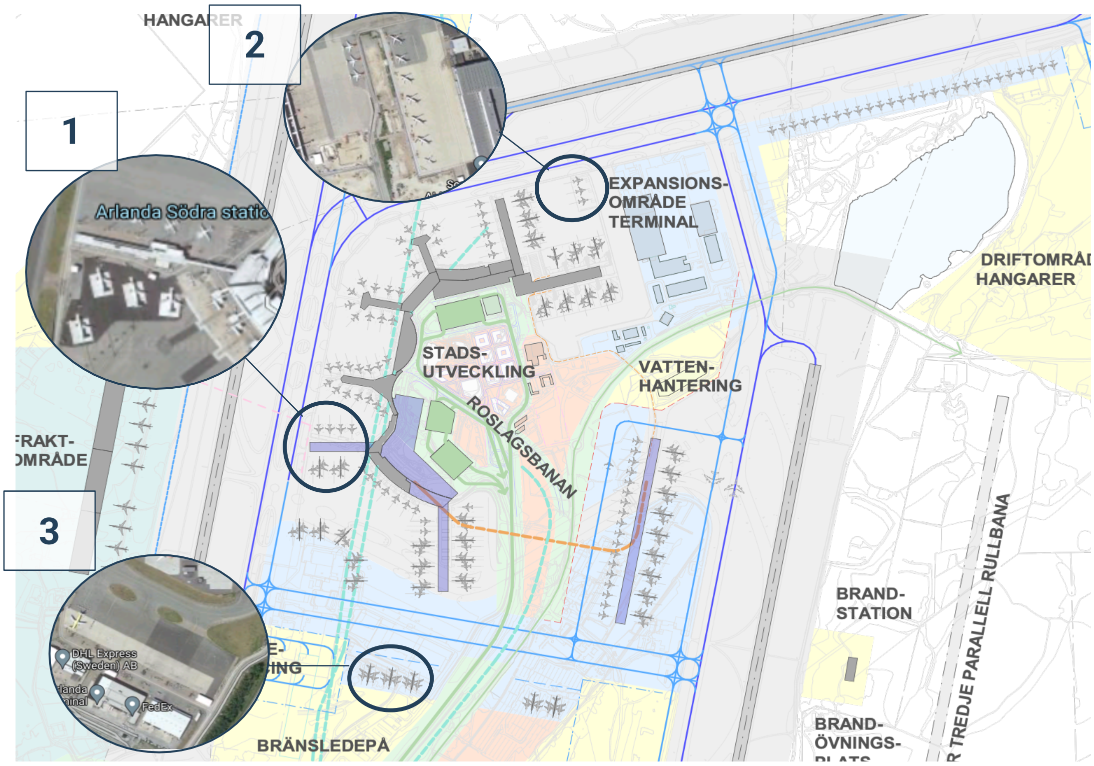



*Figure 8: Long-term optional electric aircraft placements at Stockholm Arlanda Airport*

As table 18 shows, one condition for the third option to be plausible is that the cargo area will be moved to another area at the airport (which is included in the master plan as well, as it is planned to be moved to the western side of runway 1, which is the western runway). Not having this area moved, may cause a lot of logistical problems as cargo and passenger processes will be mixed (AA1).

Currently, Stockholm Arlanda Airport sees a continuing problem with having too few remote stands, which creates a necessity to start creating infrastructure and facilities in new airfield which might even become designated electric aircraft handling areas in the long term (AA1). The challenge of electric aircraft placement at the airport is not the only factor to consider, as the infrastructure it brings with also requires a lot of space to implement at or near the platforms. Section 6.1. indicated that there is no current standardized charging equipment, which results in a lack of knowledge on the space the infrastructure will take in. Therefore, further in-depth research is needed to analyze the consequences on the space the charging and storage facilities will take in once the infrastructure is standardized.

If the safety requirements turn out to prove electric aircraft charging at the terminal unsafe, the feasibility of the first option fades and option two would be the place where electric aircraft will be placed. This remote option requires transportation between the remote aircraft and the terminal, thus added investment cost are needed for bus gates at the terminal, the actual bus transfers and of course the investment in the aircraft stands. From an operational perspective, new routes need to be specified for the bus to transport the passengers from the aircraft to the terminal (JN1).

Lastly, one point of consideration which was not included in this project scope but still vital to include in research on the airport consequences due to the introduction of electric aircraft, are the issues linked to the maintenance, MRO, processes. For electric aircraft the maintenance facilities will need to be adapted to maintain electric flights. Maintenance includes the small checks during the turn-around, but also the maintenance if there is an aircraft on the ground issue as well as the scheduled maintenance areas (GB1).

### 6.4. Chapter conclusion

With the introduction of electric aircraft, thus a new technology, the airport is required to research the needs of these aircraft and what consequences that would bring to the current infrastructure at Stockholm Arlanda airport. Airlines require the shortest turnaround time possible, thus several facilities are needed to handle these electric aircraft:

- Chargers with different power modes (for example slow, medium or high) to not over-stress the grid
- Electricity storage to cope with the peak power demands
- Cooling equipment to continue fast charging without reducing the lifetime of the battery
- Monitoring or management systems to measure temperatures and currents and monitor the battery cells' operation.
- New cable connections connecting the chargers to the main power points, or connecting electricity storage to the chargers and the main power points

The first step in the standardization and certification process of aircraft and infrastructure is to focus on small electric aircraft (like pipistrel) and eVTOLs and their charging equipment, which is now done through working groups at for example EUROCAE and SAE. Similar industries like the electric heavy truck and automotive industry can be learned from, as they are also working with megawatt-scale charging systems and have a lot of experience in working with batteries. After that, these means of compliance will be tailored and applied for regional aircraft. With standardized charging infrastructure, the airport safeguards infrastructural flexibility and synchronicity as it prevents having several chargers located at the platforms.

Operational assessments are required as electric aircraft are adapted in the current airport environment. The safety and space requirements that should be considered are the following:

- Hazard area around the electric aircraft while charging: current research is being done on the area which concerns possible hazards around a charging aircraft. The main question is whether this area causes electric aircraft to be handled at a remote area or if it is proven safe so it can be handled at the terminal, next to regular jet-fueled aircraft.
- Firefighting capabilities: firefighting equipment and training is required when this new technology is introduced
- Staff training: ground handling personnel should be trained on how to work with electric aircraft and learn about the risk areas.

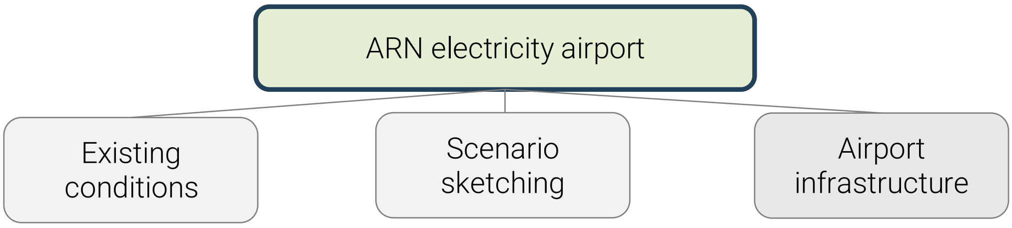
Not only aircraft manufacturers should be working closely with safety agencies. Airports, airlines and other market players should cooperate and standardize aircraft and infrastructure through testing and working together. Planning and cooperation with aircraft operators should start today to prevent patchwork approaches and to exchange knowledge and information among stakeholders. The lack of uniformity in the aviation industry is a safety concern and a risk that cannot be overestimated.

For the placement of the electric aircraft at Stockholm Arlanda Airport, three best options can be found:

- Option 1: Terminal 3 (short + long term)
- Option 2: Northern remote stands (short + long term)
- Option 3: Cargo area (long term)

If the safety requirements turn out to prove electric aircraft charging at the terminal unsafe, option 1 will not be feasible and option 2 would be the place where electric aircraft will be placed. For the long-term options, it depends whether the cargo area will be moved, as planned according to the airport's master plan. If the cargo area will not be moved, logistical challenges might prevent option 3 to be plausible.

# 7. Conclusion




The main problem centralized in this thesis are the consequences of the electric aircraft introduction at Stockholm Arlanda Airport's airside design.

This research shows that the electric aircraft developments of 19-seaters with 400 km range, 50-seaters with 1,000 km range and 100-seaters with 2,000 km range, rely on the battery technologies and aircraft capacities, which causes dependencies between the scenarios as well. The feasibility of the scenarios is influenced by several key- and external factors, which requires Swedavia to monitor actual developments closely and act accordingly together with involved stakeholders. The key factors gathered from the 2019 flight schedule data analysis, namely the weekly electric departures and the departure peaks per hour are shown in table 19.

| | High scenarios (passenger demand) | | | Low scenarios (available seats) | | |
|---|---|---|---|---|---|---|
| *Scenario* | **1** | **2** | **3** | **1** | **2** | **3** |
| Departures [week] | 86 | 364 | 1,008 | 11 | 80 | 520 |
| Peak departures [hour] | 4 | 10 | 26 | 1 | 4 | 10 |

*Table 19: Weekly electric departures and hourly peaks for scenario 1, 2 and 3*

Essential external factors to consider for the increase of expected electric aircraft numbers start with the forecast of new domestic routes, increase of passenger demand for this sustainable way of traveling and the attractiveness for the PSO routes to be replaced. However, there are also external factors that could make electric aircraft operation less attractive and decrease the expected electric aircraft numbers. The decrease would be caused by PSO routes not being replaced due to governmental conditions, current passenger demand decreases due to covid-19 and flight shaming, regional airports connecting point-to-point instead of through Stockholm Arlanda Airport, the charging time increasing the turnaround time and the development of other modes of transport like the rail network.

The expected number of electric aircraft cannot be expressed in absolute numbers yet, as it is still dependent on too many unknown factors. However, the infrastructural consequences for the airfield lay-out can be sketched in the several terms of the scenarios. One critical factor is the electricity network, which needs to supply enough demand for the aircraft to be charged at the airports. To adjust the electricity grid to the capacities required, grid enhancement, battery storage facilities, solar PV panels and vehicle to grid solutions are vital to implement. When introducing new infrastructure, especially at the platforms, standardization is the foremost important factor to avoid patch-work approaches by stakeholders. The airport will need synchronized chargers with different power modes, electricity storage facilities, cooling equipment and monitoring or management systems.

Infrastructural facilities are a first concern when considering space requirements, but safety requirements also influence the space an electric aircraft takes in. It is still unsure if an electric aircraft can be charged next to regular jet-fueled aircraft, thus at the terminal. Based on all influencing factors as mentioned above, the final aircraft placement options can be sketched.

Figure 9 shows the short-term options 1 and 2 in the map of Stockholm Arlanda Airport's current airfield, where figure 10 shows the long-term options 1, 2 and 3 in the airport's master plan for 2070.

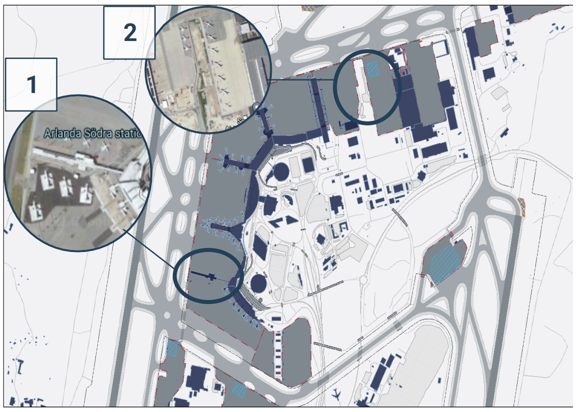



*Figure 9: short-term electric aircraft placement options*

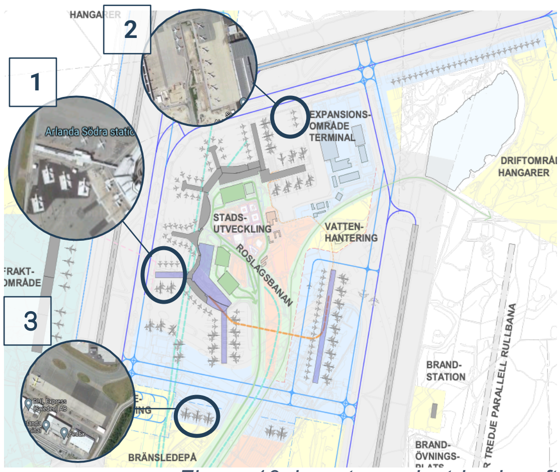



*Figure 10: long-term electric aircraft placement options*

Concluding, the introduction of electric aircraft will slowly but surely influence Stockholm Arlanda Airport's airfield design, where, especially in the beginning, investment costs will be the biggest hurdle. But the opportunity to become the most sustainable way of transportation in combination with stakeholder, political and society willingness will overrule both investment and circumstantial limits.

# 8. Discussion

This thesis focuses on the need for change in Stockholm Arlanda Airport's infrastructure due to the introduction of electric aircraft at the airport, which is supported by current aircraft developments, scenario sketching and the required infrastructural equipment. Forecasting of future traffic always brings challenges, and has many points to consider, including external factors and uncertainties which the outcome of this introduction of electric aircraft is dependent on.

Literature research showcased two possible electric aircraft technologies: battery swapping and fast charging. However, during the interviews conducted in this research, it became clear that the battery swapping technology is not being developed sufficiently for the smaller, short-term aircraft. This made the research deviate from the literature and focus on the consequences of just one technology: the fast-charged aircraft. Even though the first developments of 19-seaters are gaining momentum, the possible scenarios are highly dependent on battery technology developments. These scenarios have been sketched on the current battery technologies, but it could turn both ways: either the battery developments breaking through to greater capacities, or the technologies proving not to be worth the investment. These should be closely monitored, to create the most plausible scenarios and for Swedavia to know what and how fast the developments are introduced.

Even though the data-analysis of the current flight schedule gives a good first insight in the possible electric routes, external factors pay a big role in the determination of the number of electric aircraft movements at the airport. Due to the still unanswered questions about the passenger demand on the routes and the consequences of the other external factors (triangle flights, turnaround times, new route introductions/ substitution of current routes, the closing of Bromma airport, PSO routes and air and rail competition), the exact number of expected electric flight cannot be quantified yet. Nevertheless, it is a first step for Swedavia to have an adequate overview of the possible factors put together and to transform the consequences into numbers once research allows to do so.

Literature in chapter 2 showed a number of 100 and 186 seats for the second and third scenario. In the beginning of this research, the intention was to work with these numbers, but expert opinions during conferences, working groups and interviews stated differently. Therefore, the decision has been made to work with lower seat numbers, to increase the plausibility of the scenarios sketched in the research. Furthermore, the ranges taken during the scenarios have been applied according to the great circle distance of the routes. Flight paths, weather conditions and alternative airports can cause the actual flight range of the aircraft decrease, which may change the indicated destinations in the scenarios.

In addition to the dependency of the scenarios sketched, the advancements of the infrastructural technologies and charging facilities influence the probability of the introduction of electric flight greatly. To make operation by electric aircraft attractive for aircraft operators, aircraft need to be fast-charged during the turnaround process, but cannot require too much power as it might over-stress the grid. The grid should be enhanced in time for aircraft charging to become feasible, just as battery storage facilities, solar PV panels and other solutions like vehicle to grid should be implemented to cope with the power demand peaks.

The main research question is concerning the airfield consequences due to the electric aircraft introduction. However, the exact space the aircraft will take in, as well as the required space for the facilities, are yet unknown. The hazard area around the aircraft could influence the placement of the aircraft at the airport greatly, which requires more research. Even though the specific space requirements remain uncertain, two short-term options and three long-term options for electric aircraft placement at the airport could be identified.

Even though there are many fragmented challenges concerning all stakeholders, one main opportunity arose during this research: there is a fantastic amount of willingness from all parties involved to make this way of sustainable aviation work. The challenges are big, and the investments are high, but these can be overcome by cooperation, collaborated testing and knowledge sharing, which is already done greatly. This new development starts with small steps, and based on these experiences, the testing on larger scales can be done when aircraft developments allow to do so.

# 9. Recommendations

To initiate cooperation and start testing the consequences for larger airports like Stockholm Arlanda Airport, the following points are recommended for further research:

Short-term

- Further define, together with stakeholders, actual passenger demand numbers due to new routes and competitiveness with point-to-point flights and rail networks.
- Determine (for the current capacity numbers but also expected post-pandemic capacity numbers) if it is reasonable for Aranda to have smaller electric aircraft occupy the stands longer in comparison to the larger and quicker aircraft.
- Define the safety impact of the electric aircraft during the turnaround process, the size of the hazard area around the aircraft and whether passengers can board while charging.
- Continue research on the production of electricity at the airport through Solar PV panels and the vehicle to grid solution
- Determine the need for one large or multiple smaller battery storages according to the airlines' turnaround needs and the feasibility of locating these facilities at airside. If it cannot be placed at airside, research the possibility to transport the electricity from landside to airside including the required voltage to transport and the according losses.
- Define the influence of the charging times, thus turnaround times, on the attractiveness for aircraft operators to operate with electric aircraft.
- Specify firefighting standards and establish staff trainings to safely handle electric aircraft.
- When the aircraft developments allow to do so, start infrastructural tests on larger scales to assess the charging consequences on the power demand, electric aircraft handling processes and space impacts at the airport due to safety constraints.
- Research the consequences of hybrid, hydrogen and fuel cell technologies as these impact the power demand and airfield space as well.

By implementing these recommendations, Swedavia's main airport Stockholm Arlanda has the opportunity to handle battery-electric aircraft and support the change towards the most sustainable way of transportation.

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# Appendices

*Appendix I: Reflection*

The writing of this thesis was a very exciting process, as it was a great opportunity to perform research on a topic related to my personal interest. The 4-year background in aviation logistics triggered the interest to research this new segment from a general point of view, including the many stakeholders and supporting ecosystem to make the electric aviation work.

At first, I intended to find all the answers to the main research question and sub-research questions I stated, but after the first round of interviews, I started learning about all the yet unanswered questions, which influenced the outcome of my research as well. I started to understand how there is already a big network of stakeholders working together on these questions, and how some questions are answered quicker than others.

The current challenge we see due to covid brought its challenges and opportunities, as writing the thesis from home would be another setting than usual when working together and gathering information through interviews. However, since all meetings were now held online, I had the opportunity to speak to a large number of Swedavia colleagues and electric aviation stakeholders outside Swedavia, meanwhile working from Amsterdam. The amount of willingness to cooperate in this thesis, as well as in the electric aviation segment is incredible.

In terms of research skills, it was very interesting to work with this many interviews and to also do the focused group interview for the first time. It was an interesting challenge to lead an online discussion, as this was the first time I ever set up this kind of group interview. Nevertheless, it turned out great and it was a very good way to validate and discuss the outcomes of the scenarios and space requirements research. In addition, I can say that my English writing skills, planning skills and data collection and analysis skills improved during this thesis.

Looking back at the start of this thesis period, I started with hardly any knowledge on the progress of this new segment and all the challenges and technical developments that come along. The intention of the thesis process was to learn more about this way of transportation and the feasibility of it. I can say that this goal has been reached largely, especially due to the extensive conversations I had the chance to have, and it is great to see how much knowledge I have gained on this subject in 'just' these five months.

Overall, I can look back at this thesis writing as a very positive process, where I learned a lot on a personal, as well as on an academic level.

*Appendix II: Medium- and heavy-duty electric vehicle charging*

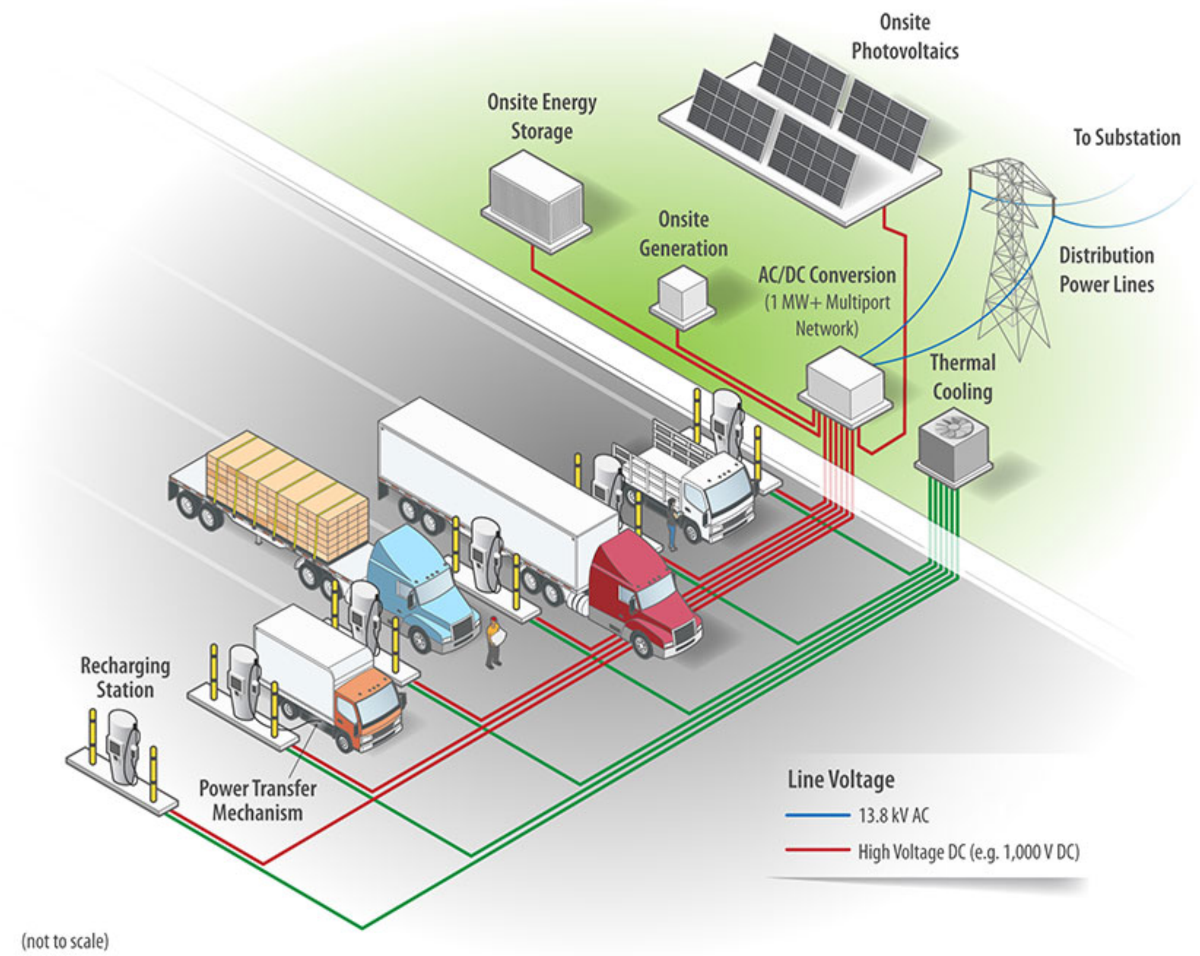


*Figure 11: Medium-and Heavy-Duty Electric Vehicle Charging (Source: nrel.gov)*

AVIATION ACADEMY

Amsterdam University of Applied Sciences

Swedavia Airports