Airport Charging System Designs and Power Management for Megawatt-Level Charging of Battery-Electric Aircraft

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Abstract

The adoption of electric aircraft (EA) offers notable environmental advantages by mitigating greenhouse gas emissions and enhancing regional accessibility through reduced operational costs. Despite these benefits, EA faces significant challenges, partly in achieving practical operational ranges and developing robust airport charging infrastructures. The infrastructure challenge is compounded by the need for rapid turnaround times (TAT) in regional aviation, requiring high-power charging solutions above 1 MW. This paper explores various topologies for EA power supply systems and discusses pros and cons with those. Furthermore, an optimization model is developed using quadratic programming (QP) to allocate charging power among multiple aircraft, ensuring efficient and reliable operations under different system configurations. Simulations evaluate the performance of these configurations, highlighting the impact of grid power capacity, dimensioning of battery energy storage systems (BESS), and number of charging stands on system feasibility. The findings in this paper provide a foundational framework for designing airport infrastructures capable of supporting a growing demand for electric aviation, ensuring efficient power management and minimal operational disruptions.

Keywords: electric aircraft, airport design, high-power, charging infrastructure, optimization

1 Introduction

Electric aircraft (EA) represent a significant advancement in aviation technology, offering potential environmental benefits by reducing greenhouse gas emissions, as well as increasing regional accessibility for people and businesses as an effect of lower operating costs [1].

When considering the maximum take-off weight of current aircraft models and accounting for the operating empty weight and payload, earlier studies suggest anywhere from 100–500 km operational range, depending on the available battery technology today and in the foreseeable future. This range accounts for reserve requirements, including loitering and reaching alternate destination airports [2]-[5]. To extend the operational range, EA can adopt different hybrid configurations, e.g. using jet fuel for the mandated reserve capacity, and as a range extender to provide additional power beyond the battery capacity. Achieving a practical operational range and covering most of the travelled kilometers using battery energy will likely require EA to carry MWh-level battery pack capacities. Larger aircraft models and future battery technologies may even necessitate even higher figures, as increased specific energy translates to lighter batteries and the possibility of adding more kWh's to the aircraft [2].

The challenge in electric aviation extends beyond the aircraft themselves to encompass the development of airport infrastructure capable of handling charging needs. To retain commercially viable economics for the airlines, EA will need to adapt to short TAT, particularly in the context of regional aviation, since TAT has a larger relative impact on the total downtime of the aircraft there. Figure 1 shows the distribution of time between arrival and next departure for over 500,000 commercial passenger aircraft visits at Swedish airports from 2019 to 2023. The median duration was 62 minutes, but this value decreases to 48 minutes if Stockholm Arlanda Airport is excluded, which is the largest airport, accounting for approximately 40% of the annual departures in Sweden (based on data from LFV). Furthermore, it is important to recognize that the actual TAT is smaller, since it excludes time spent taxiing between runway and the gate. According to EUROCONTROL, the average taxi-in time (from runway to gate) for intra-European flights was 6.1 minutes, while the average taxi-out time (from gate to runway) was 12.2 minutes in 2022 [7]. For smaller airports with less flight activity, these taxi-times can likely be further reduced. However, a reasonable assumption for TAT would be 30-40 minutes, which corresponds to the time between the aircraft being "in-block" (arriving at the gate) and "off-block" (ready for departure) at the gate.

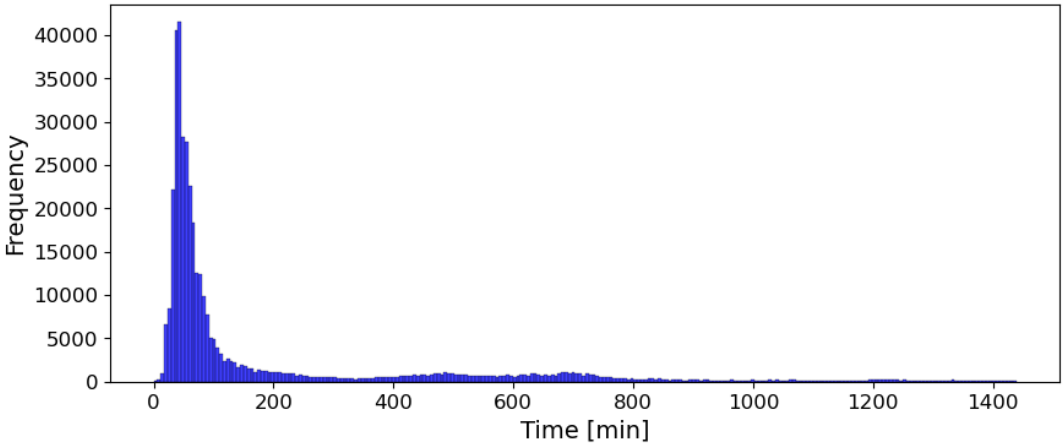


Figure 1 – Distribution of time between arrival and departure for over 500,000 aircraft visits at Swedish airports from historical data between year 2019-2023. Only the distribution of values less than 24 hours (1440 minutes) is shown in the figure for visualization purposes.

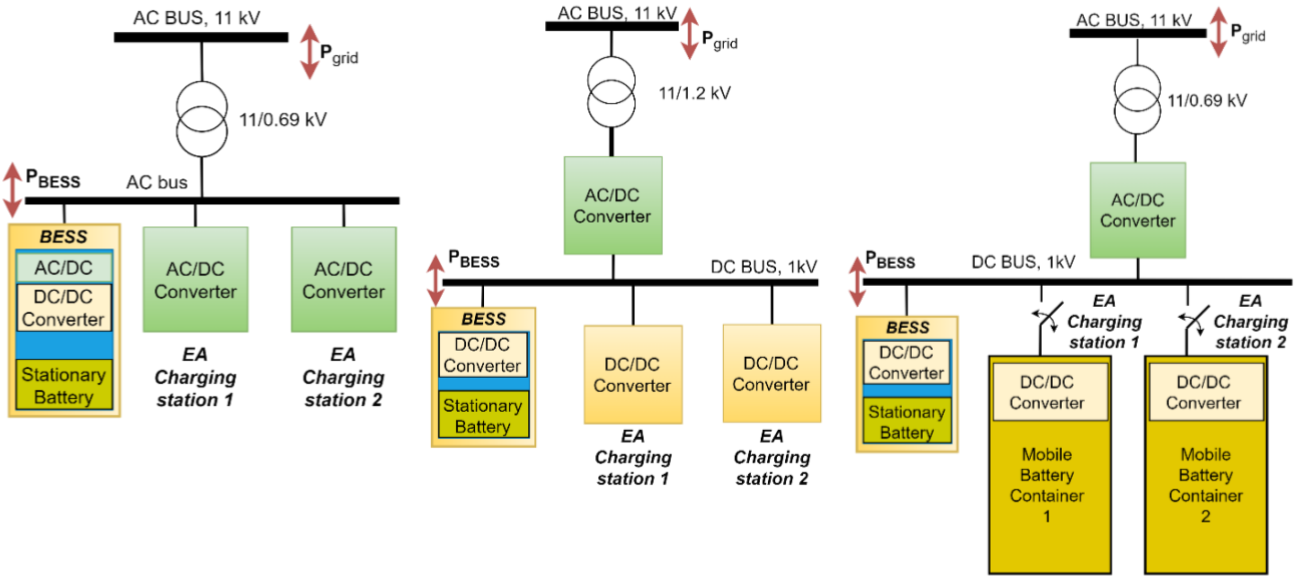
The combination of short TAT and large battery packs necessitates robust high-power charging solutions, e.g. at least 1.5-2 MW for recharging of a fully depleted 1 MWh battery pack for 30-40 minutes TAT. Earlier research papers have explored battery swapping systems as a viable solution to reduce downtime and improve the operational efficiency at airports [8][9]. This paper focuses on EA equipped with fixed, non-swappable batteries. We delve into potential topologies for the power supply system and tackle the charging dispatch problem, exploring how to effectively coordinate the simultaneous charging of multiple aircraft. While this issue remains relatively novel in aviation, analogous challenges have been studied in the context of electric vehicles [10]-[12].

2 Airport charging system topologies

Given that different airports have varying prerequisites for connecting the necessary power supply and infrastructure to facilitate EA, it is essential to investigate multiple system design options. The preferred solutions may differ depending on whether an airport has significant over-capacity available or if the surrounding electricity grid can accommodate an increased power supply within reasonable timeframes. Since today's airports were not constructed with EA in mind, this situation presents a valuable opportunity to reconsider how power supply can be most effectively secured. Most certainly, there is no universal solution that fits all scenarios, which is why this section outlines various possible topologies, including their advantages and disadvantages.

The aim is to evaluate the topologies based on:

- **Scalability:** How well does the solution scale from a small, to regional to country hub. What limits the power or energy transfer from grid connection (gc).
- **Charging system efficiency:** Focusing on conversion losses.
- **Reliability:** How susceptible is the system to faults, disturbances and increased complexity.
- **EMC:** Due to the EMC impact on analogue communication is a concern from airport owners, the possibility to shield or protect from possible EMC radiated sources is considered as well as placement.
- **Cost:** An overall cost estimate for various components.



First topology (TP1), consists of AC connected chargers with an optional BESS to manage grid and transformer constraints during high power charging.

Second topology (TP2), consists of a main DC-bus and a BESS to manage possible constraints in grid, transformer, or the main AC/DC converters.

Third topology (TP3), consists of a DC-bus for charging of mobile battery containers, that then replicate the charging of the EA with that of a conventional fuel truck.

Figure 2 – Proposed topology alternatives for the electrical system at the airport for accommodating EA charging.

The main target is not to present voltage levels in detail, though they have large impact on the losses, especially during transmission of the charging power to EA charging stations, or internally within AC or DC distribution grids at the airport. All EA charging stations in Figure 2 are meant to allow for Megawatt Charging System (MCS) [14], utilizing up to 1250 VDC and up to 3000 A per EA charging station. The first topology (TP1) is perhaps the simplest and could be expanded with an AC coupled battery energy storage system (BESS) if the grid capacity or transformer capacity is limited for shorter or longer periods of time. Power transfer issues could be a result of maintenance, faults, or rapid expansion of electric loads at the airport. Considering energy efficiency to charge the EA from energy stored in the BESS the conversion losses would notable due to a roundtrip efficiency of perhaps 90% in the BESS. If a battery is needed multiple times for managing grid congestion and has multiple daily cycles it could be worth considering the second topology (TP2). In TP2, the batteries are DC-connected to a common DC bus with relatively higher voltage levels, this reduces the conversion stages from battery to EA but introduces a main converter(s) (usually several in parallel) to maintain and convert the energy to the DC-bus. Generally, AC/DC conversion suffers from lower efficiency than DC/DC conversion. All converters are assumed to be several in parallel. The third topology (TP3) is mimicking today's refueling of conventional aircraft, mobile battery containers are driven from a charging location to the aircraft and used for charging the EA battery through an DC/DC converter, in the mobile battery container. TP3 can also be expanded with stationary DC EA charging stations as in TP2 if needed. The mobile battery containers in TP3 would need to restrict their height to comply with refueling trucks height limits.

The BESS in all cases could if needed provide other features for the airport such as ancillary services, peak shaving, island operation or flexibility for energy to local markets when not used for managing the EA charging. DC system bus could also easily integrate PV assuming such components would pass EMC requirements.

Table 1 - Pros and cons related to presented topologies, with or without (w.o) and power or energy limitations at grid connection (gc).

	Scalability	Efficiency	Reliability	EMC	Cost
TP1	Limited to gc energy, good scalability.	Multiple AC/DC conversions	Proven solution, usually few or 1 transformer	AC/DC converter close to EA	High
TP1 w.o. BESS	Limited to gc power.	Depends on AC voltage level, high efficiency in transformer.	Few components, low complexity	Few components, AC/DC converter close to EA	Relatively low
TP2	Limited to gc energy, good scalability.	Depends on main AC/DC conversion and AC voltages	Increased reliability due to parallel converters	DC/DC converter close to EA	Higher
TP2 w.o. BESS	Limited to gc power	Higher than TP1 w.o BESS.	Increased reliability due to parallel converters	DC/DC converter close to EA	High
TP3	Limited to energy transfer at gc. Good scalability.	Lowest system efficiency, due to multiple batteries.	Increased reliability due to parallel converters, and mobile chargers	Container provides shielding	Highest
TP3 w.o. BESS	Limited to gc power. Good scalability.	Low system efficiency, no path without battery conversion stages.	Increased reliability due to parallel converters, and mobile chargers	Container provides shielding	Higher

3 Power optimization objectives

When selecting the topology and determining the dimensions of the various components of the power supply and charging system for EA at an airport, it is crucial to incorporate perspectives on energy- and power management. While it can be relatively easy to predict the needs and perform optimal charging for a single aircraft, scaling the system to handle a fleet of EA is much more complex. This scaling introduces more degrees of freedom in the charging process, particularly in prioritizing power supply among multiple aircraft. Additionally, airports should explore the potential for managing the charging of multiple aircraft within constraints such as installed capacity, the number of available charging stations, and TAT limits for the charging process.

This paper presents an optimization method for the coordinated charging of multiple EA and evaluates system performance. The focus is on topologies TP1 and TP2, as the developed optimization algorithm currently includes the functionality to provide power supply directly from the electric grid, via a BESS, or a combination of both. However, the method is also applicable to the TP3 topology, although additional functionality is required before that system can be effectively managed.

From now on, the paper will assume that either topology 1 or topology 2 is applied. These topologies are described in Chapter 2.

The objectives of this section are:

O1. To formulate a charging algorithm that proposes a reference power for each EA undergoing charging.

O2. To conduct a simulation analysis to apply and test the efficacy of the proposed charging algorithm.

O3. To evaluate a set of proposed designs and dimensioning cases for electric airport infrastructure.

The evaluation in O3 may reveal the shortcomings of a proposed airport design in supplying sufficient charging power to an incoming fleet of EA, or it might indicate when a system is oversized. While the primary aim is not to develop a real-world controller for the coordination of the charging process, the ideas presented in this paper can serve as a foundational framework for such a controller. Furthermore, although minimizing costs associated with power losses and battery degradation is desirable, this aspect is not the primary focus of this paper.

4 Power optimization methodology

The primary contribution of this work is the development of a mathematical model for allocating a constrained power supply across multiple aircraft. The initial focus is on explaining the simulation of the airport's charging infrastructure and processes.

4.1 Aircraft charging simulation

The pseudocode in Algorithm 1 outlines the primary steps involved in the charging simulation. These decisions are informed by multiple states of each aircraft, including (i) State of Charge (SoC), (ii) remaining TAT before next departure, (iii) minimum and maximum battery power capacity, and (iv) battery energy capacity. In addition to the states of the aircraft, the airport's power capabilities need to be known, as well as the power capacity of the EA charging station. The power allocation (split) among aircraft being charged is determined with respect to these states. This is achieved using the '*calculateSplit()*' method in the pseudocode, enabling a full day of airport operations to be simulated. Such a simulation allows for the evaluation of airport design by specifying parameters like power capacity.

Algorithm 1 – Simulation pseudocode. The term ***s*** is states, and ***pr*** is power reference.

```
time = 0
while (TAT not exceeded)
    s = readStatesInCraftsBeingCharged()
    pr = calculateSplit(s)
    applyReferencePowerLevelsOnCraftsBeingCharged(pr)
    moveCraftsInQueueAndCraftsFullyCharged()
    moveCraftsInAir()
    time = calculateNewTime(time)
end
```

Figure 3 illustrates an example of an airport state where a single aircraft is being charged. There airport features three charging stations (stands), represented by the lower row of grey squares. The leftmost square represents queued aircraft. In this example scenario, the power supplied to the aircraft is solely restricted by the capacity of the charging station, which was set to 2000 kW. An underlying parameter assumption, not shown in Figure 3, is that the electricity grid can supply a maximum of 1500 kW for EA charging. Therefore, the BESS compensates by providing an additional 500 kW. Consequently, the total power capacity available for charging all aircraft at the airport is the sum of 1500 kW from the grid, and 4934 kW from the BESS[1].

Figure 3 – Airport state 1. Single aircraft charging. The term *req. p* (downmost aircraft progress bar) represents the required charging power. Power and power capacity (PC) is given in the unit kW. The term *time* is the elapsed time, in minutes. The total elapsed time in the simulation is given in the upper right corner of the figure, in hours. The term *soc* is the aircraft battery SoC, in %.

[1] BESS energy capacity is 20 MWh, for this specific simulation.

To show the implications of a weaker grid connection, an alternative airport design is presented in Figure 4, featuring a reduced total power capacity (*pwr cap*) of 2428 kW. The figure depicts such a system attempting to charge two aircraft simultaneously. The central question that arises is how much power should be allocated to each aircraft. As seen, in this specific state, the aircraft with ID “4379a” receives a higher power allocation, though how much higher and why highlights the complex issue of power distribution prioritization, which is discussed in more detail in the next section.

Figure 4 represents an undesirable failure state where only one minute of TAT remains for the aircraft “4379a”, and it is not fully charged (here defined as SoC=99%). The red progress bar indicates that the required power to be charged within the reaming timeframe exceeds the power capacity of the charging station.

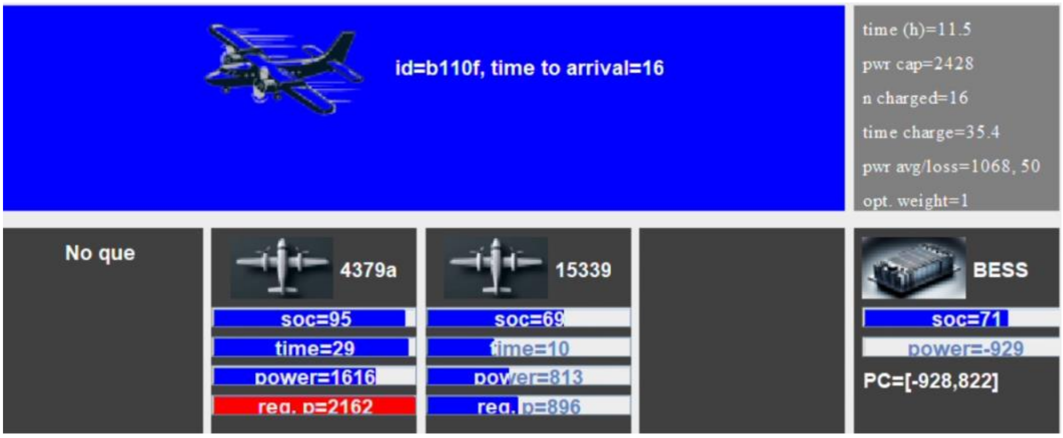


Figure 4 – Airport state 2. Two aircraft being charged simultaneously, sharing a reduced total system power capacity compared to airport state 1 in Figure 3. A failure state is observed with the current system settings.

There are several modeling aspects that are not explicitly depicted in Figure 3 and Figure 4. One such aspect is the aircraft battery’s state of power. As the battery approaches a fully charged state, the charging power is constrained by the battery's inherent power capacity. Generally, a battery with a low SoC can accept a higher charging power compared to a battery with a high SoC. Further details on SoC-dependent power capacity are provided in Appendix B.

4.2 Optimization problem

The charging problem is mathematically expressed as a QP optimization problem in equation (1). This problem is solved for every time step, i.e. multiple times during a simulation. One minute is used as the time step setting. For details about QP, see Appendix A.

$$\begin{aligned} min\,cost(P) &= -k' \cdot P + \frac{1}{2} \cdot P' \cdot Q \cdot P \\ &= -[k_1 \quad \dots \quad k_n] \cdot \begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} + \frac{1}{2} \cdot [P_1 \quad \dots \quad P_n] \cdot \begin{bmatrix} q_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & q_n \end{bmatrix} \cdot \begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} \end{aligned} \tag{1}$$

w.r.t. to constraints in Table 2.

Table 2 – Constraints for the objective function of the charging optimization.

Nr	Expression	Description
1	$\sum_i P_i \leq P_{ramp\ max}$	Limitation for the total power capacity available to all airport stands.
2	$P_i \leq P_{max}$	The charging power applied to each aircraft is limited by the power rating of the connector, or the aircraft battery power capacity.
3	$P_i \leq \begin{cases} 0 & (SoC_i(t) \geq SoC_{tar}) \\ P_{max} & (else) \end{cases}$	Power shall be zero if SoC at time *t* is above target, i.e. charging is completed.
4	$P_i \geq 0$	Only charging is allowed

The expressions in Table 2 describe the bottlenecks and desired charging behavior. An example of a bottleneck is that the required power to a specific aircraft i is restricted by either the connector or the battery's power capacity, as described in (2). Discharge of the aircraft is not allowed.

$$P_{max} = min(P_{connector\ max}, P_{battery\ max}) \tag{2}$$

The reference charging power for an aircraft is denoted as P_i, where positive power indicates charging. As expressed in (1), there are q_i terms in the diagonal of the Q matrix. The term q_i is inversely proportional to the future required charging power, as shown in (4) and (5) . The underlying logic is to prioritize aircraft that have a high remaining energy demand, and a low remaining time to charge. This prioritization is represented by the vector q. If q_i is small, it will not act as a 'damping' factor, resulting in a large P_i. This rationale motivates (3), where the function $invert$ inverts all values. For instance, [0.2,0.5,0.3] → [0.48,0.19,0.32]. This inversion ensures that a small q_i value corresponds to a large prioritization p_i, and vice versa.

$$q = invert(p) \tag{3}$$

When controlling the charging of aircraft, it is desirable to minimize the future required charging power, denoted as rp. Consequently, a large prioritization p_i and a high charging power P_i are preferred for an aircraft if its rp is substantial. This logic motivates 0.

$$p_i = rp_i / max\ (rp) \tag{4}$$

$$rp_i = E_{rem\ i}(t) / t_{rem\ i}(t) \tag{5}$$

The previous mathematical reasoning, described in (3)-(5), can be summarized as; if power capacity is a scarce resource, it is desirable to allocate higher charging power to those aircraft that are in a bad state. In this context, a bad state refers to having a significant amount of remaining energy demand and a short remaining time for conducting the charging.

The term w in (6)[2] is a weight factor for power loss versus charging time.

$$k_i = w \cdot P_{nom} \tag{6}$$

A positive w means that discharging is not possible or allowed. If w is close to zero, minimizing power loss (low charging power) will be prioritized. Conversely, if w is large (approximately 1), time will be prioritized, and only power capacity limitations in the system will be a restriction. Prioritizing time thus imply higher charging powers. The minus sign in the linear term, $-k' \cdot P$, has a simple motivation. The objective is to maximize positive P_i values, which is equivalent to minimizing negative P_i values.

5 Example analysis

An example analysis is provided to enhance the understanding of the split algorithm discussed in the previous section. Figure 5 demonstrates the application of the split algorithm from (1), with an assumed weight w of one, and maximum TAT of 30 minutes for charging. The following comments and observations can be made from the used example:

- Both total power and individual slot power limits are respected (upper row plots).
- At 0.7 hours, two aircraft require charging, triggering the split prioritization mechanism. The newly arrived aircraft receives a higher power supply, highlighting the urgency of charging aircraft with higher energy needs (upper left plot).
- The number of aircraft simultaneously present at the airport varies between 0-2, and the maximum allowed charging time of 30 minutes is never exceeded, indicated by the purple line ("*Time exc.*") never being bigger than zero (lower left plot).

[2] $\mathrm{P_{nom}}$ is similar to the desired P_i. This can be realized from the 1d case. Assume $f = P^2 - k \cdot P$. Derivate f w.r.t P, and one gets $2 \cdot P - k$ which has solution (optimal point) $P = k/2$.

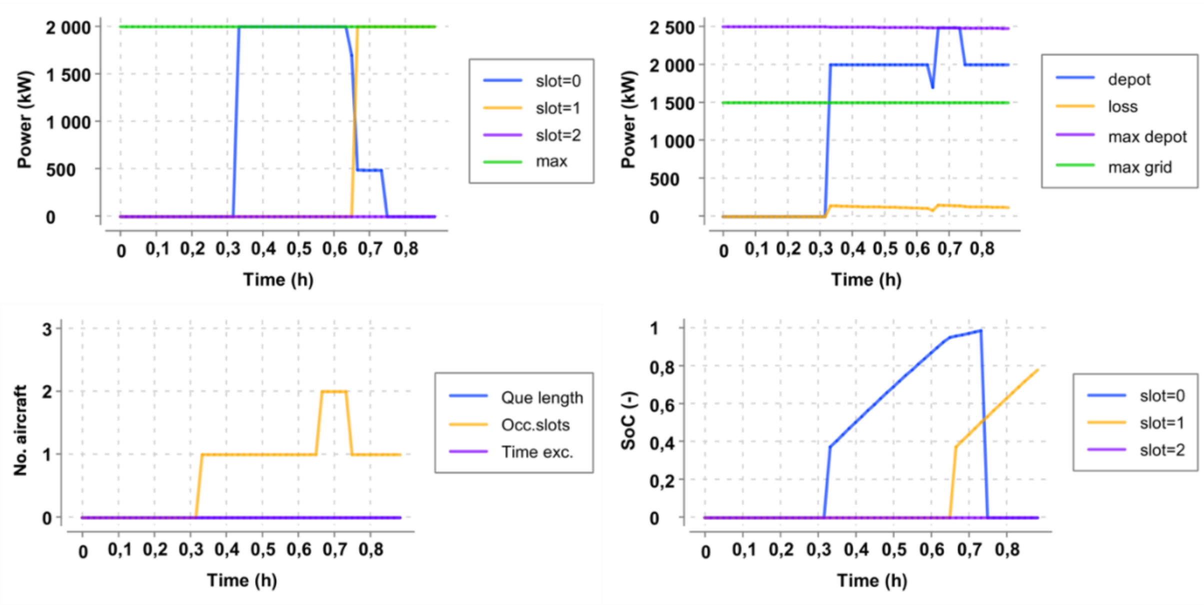


Figure 5 – Example of the resulting system performance using the split algorithm to charge 0-2 aircraft simultaneously. In this case, the TAT was set to maximum 30 minutes, and weight w was set to one, meaning that minimized charging time is prioritized.

6 Design evaluation

An evaluation of various airport designs is conducted through multiple simulations, following the pseudocode in Algorithm 1. A sensitivity analysis is performed by varying the *BESS power capacity*, *grid power capacity* and the *number of stands* available. The objective is to identify what combinations of parameters that result in an insufficient airport charging system design for incoming EA requests. The previously illustrated state in Figure 4 is an example of a situation where a charging request is not adequately met. By examining these factors, the goal is to optimize the airport designs to ensure reliable and efficient charging systems that accommodate varying demands.

6.1 Parameter setting

The parameter settings used in the analysis are presented in Table 3 and Table 4.

Table 3 – Airport parameter settings. (DS = "defined in scenarios").

Parameter	Value	Description
nStands	DS	Number of stands (locations where EA can be charged).
timeChargeMax	30 min	Maximum allowed TAT available for charging.
powerGrid	DS	Grid power capacity.
powerBESS	DS	BESS power capacity.
powerNeedAirport	500 kW	Expected airport power need, upper estimation.
powerRampMax	2 MW	Maximum power capacity to the ramp.

Table 4 – Aircraft parameter settings.

Parameter	Value	Description
energyCap	985 kWh	Battery energy capacity.
powerCap	3.7 MW	Battery power capacity.
Mass battery	4200 kg	Battery mass estimation, only including cell mass.
nCells	60 k	Number of battery cells.
energyNeed	2-3 kWh/km	Average energy consumption.
socFullyCharged	99%	Threshold for when an aircraft is considered fully charged.

Timetable data used for the analysis is presented in Table 5, where arrival times are based on a real-world schedule for turboprops at a major Swedish airport. As the table suggests, there are 26 arrivals during this day, none between 23:50 and 06:30. The consequence is that approximately one aircraft arrive every hour, but during some periods, for example around 07:30, the traffic is more intense.

Table 5 – Example timetable data for aircraft arrivals used to evaluate the airport design using the optimization method. Maximum TAT was set to 30 minutes from arrival (for simplification, arrival time is handled as arrival to gate, i.e. after taxi-in from the runway).

Arrival ID	Arrival time	Distance travelled (km)	Arrival SoC	Arrival ID	Arrival time	Distance travelled (km)	Arrival SoC
642d6	06:30	150	54%	aacd3	14:25	150	54%
addd0	06:50	150	54%	9228c	16:45	250	54%
c6243	07:10	250	24%	1491d	16:50	150	54%
3bb88	07:35	250	24%	ecd60	16:50	250	24%
41d5c	07:35	250	24%	b7ab5	17:30	250	24%
fa37b	08:10	250	24%	074b1	17:50	150	54%
af5df	08:20	250	24%	a2658	18:15	250	24%
b04d1	09:20	250	24%	4fc89	20:15	250	24%
b92e3	11:15	250	24%	f018d	20:30	150	54%
b57ce	11:25	250	24%	7c1f7	20:35	250	24%
adfee	11:25	150	54%	526d2	20:45	150	54%
2ad95	13:45	250	24%	e8bde	21:00	250	24%
21b42	14:10	250	24%	eee39	23:50	250	24%

6.2 Example of failing design

A failing design is characterized by inadequate power capacity in the charging system, as illustrated by Figure 6. The upper right plot shows that the total charging power often gets saturated. This leads to exceeded TAT's, resulting in all stands (charging stations) becoming occupied after a few hours. When the stands are full, newly arrived aircraft are placed in a queue. This unwanted situation is shown in the lower left plot of Figure 6. The two upper plots reveal that the power available to each aircraft decreases as more stands get occupied. Based on these observations, a criterion for evaluating a failing design at a specific time can now be formulated:

$$isFail = nQueue > 0 \text{ or } nTATexc > 0 \tag{7}$$

An evaluation is considered a failure if this criterion is true at any time. This means that a design is failing if, at any time, there is a queue, or any aircraft exceeds its TAT limit available for charging.

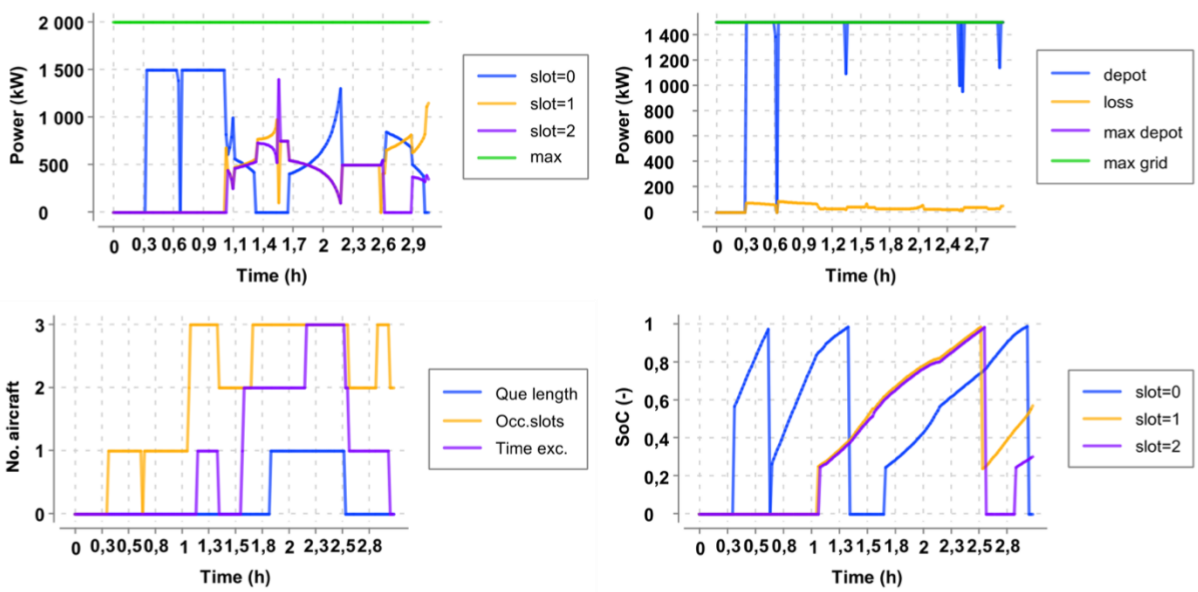


Figure 6 – Example of a system performance evaluation resulting in a failed state. Compared to earlier examples, the total power capacity available is lower.

6.3 Scenario evaluation

A sensitivity analysis is conducted, focusing on the parameters of BESS size, grid power capacity and the number of stands. The primary aim is to observe trends in how these parameters correlate with the feasibility of a design, rather than to pinpoint exact numbers. This study demonstrates the practical application of the method proposed in earlier sections of the paper, serving as a support tool for designing airports for EA. It is important to note that some of the input data are rough estimations, thus the results should be regarded as indicative rather than definitive.

A scenario corresponds to a specific parameter setup, with the studied scenarios presented in Table 6. Broadly speaking, the total system power capacity increases with the scenario index. For instance, in scenario 1, the total system power is 2 MW, whereas in scenario 12, it is 9 MW.

Table 6 – Scenarios.

Parameter/scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
powerBESS (MW)	0	0	0	0	1	1	1	1	5	5	5	5
powerGrid (MW)	2	2	4	4	2	2	4	4	2	2	4	4
nStands	3	5	3	5	3	5	3	5	3	5	3	5

For every simulation, the SoC upon arrival for each aircraft is calculated based on the distance flown and an assumed energy consumption per kilometer. Consequently, a higher relative energy consumption results in a lower starting SoC. A lower starting SoC is more demanding for the airport due to the fact that more power must be delivered within the same timeframe.

The results are presented in Figure 7, where colored bars represent scenarios with failed evaluations. In the case of the lower assumed energy consumption of 2 kWh/km, the evaluation fails only in scenarios 1 and 2. As scenario 2 fails despite an increased number of stands, as detailed in Table 6, it indicates that having many stands is ineffective if the power capacity is too low.

For the higher assumed energy consumption of 3 kWh/km, only the high-power scenarios are successful. This highlights the importance of developing accurate aircraft performance models, as energy consumption has a large impact on the dimensioning and design requirements of the airport charging system. Scenarios 9 and 10 show that a large BESS can compensate for an undersized electricity grid connection, where the former is further detailed in Figure 8, including the charging/discharging behavior of the BESS.

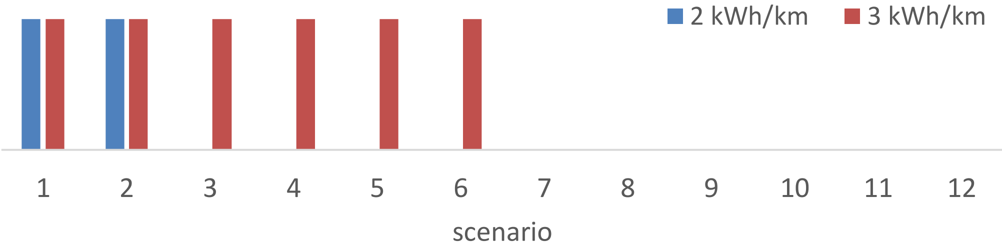


Figure 7 – Evaluation of scenarios 1-12 in Table 6. Each scenario was evaluated using two different energy consumption values for the aircraft. A visible bar corresponds to a failed evaluation for the scenario with the representative energy consumption value. No visible bars means that the scenario was successful to meet the charging demand for all aircraft without violating any of the criterions defined in (7).

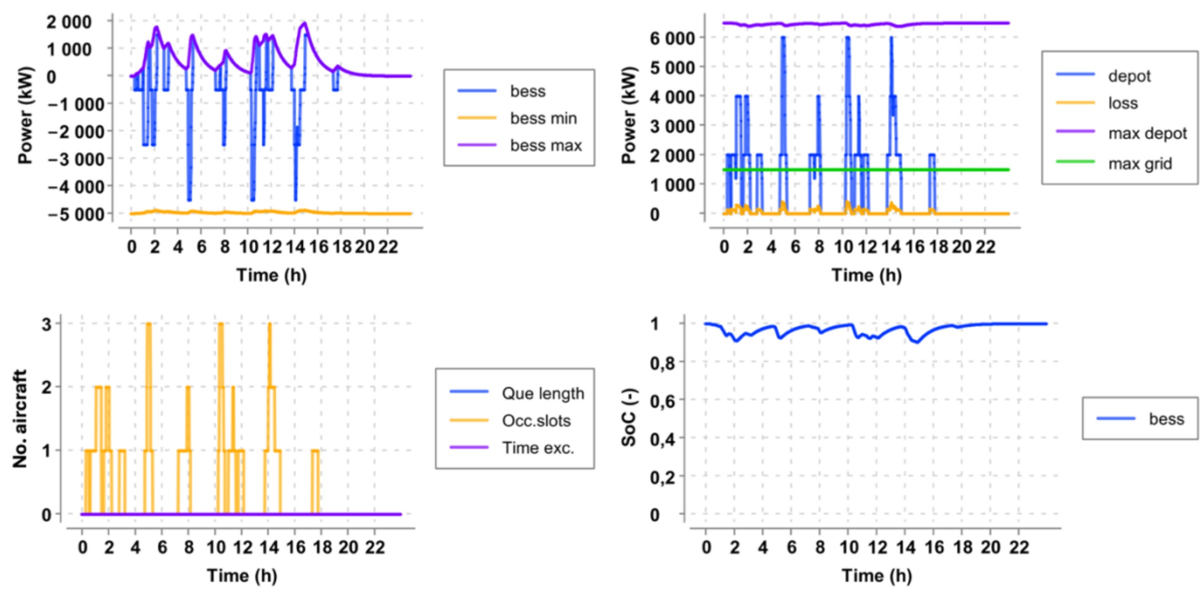


Figure 8 – Detailed results for scenario 9 in Table 6, with lower grid power capacity and large BESS. It is shown that a large BESS can offer a good alternative from a system performance perspective, if grid capacity is limited.

7 Conclusions

A novel method for coordinating power between electric aircrafts has been proposed. The innovative approach of incorporating a charging prioritization measure to influence the diagonal elements of the Q matrix in a quadratic programming formulation is, to the author's knowledge, unique. This results in a fast simulation, requiring only a few seconds on a standard personal computer to simulate a full day of airport operation. The set of example analyses presented in this paper demonstrates the complexity of designing the charging infrastructure for EA at an airport. It underscores that design variables, such as the power capacity of the electricity grid, are very challenging to determine intuitively. An extensive analysis based on simulation and power split optimization is needed to avoid a poor, suboptimal design. The main contribution of this paper is a method that performs such an analysis in a data-driven and objective manner. One indication is that a BESS can be a necessary complement, especially if the grid power capacity is insufficient. This highlights the need for a holistic approach to infrastructure design, ensuring that all components work together to meet the operational demand of EA efficiently. As shown by the various charging topologies, the power limitations or energy limitations can come from various components and are important to consider in the objective function for charging, but a key to consider for the expansion for future EA at airports.

8 Future work

Some of the data used for analysis are currently best estimates, partly to avoid revealing sensitive information. A future undertaking will involve repeating the analysis with updated and accurate data. Another important consideration regarding data setting, is that the analysis presented should be viewed as a special case. It would be valuable to explore how different timetables would affect the design. For instance, how should airport design parameters be adjusted if a more intense schedule of aircraft arrivals is anticipated? When it comes to charging, one extreme is to charge as quickly as possible, with the highest possible power at all times, while the other extreme is to use very low charging power. All analyses in this paper have assumed the former extreme, implemented by setting the weight factor defined in Section 4.2 to one. However, this approach can be considered suboptimal. High charging power introduces unnecessarily high losses in the batteries of the aircraft, as well as in the BESS, and cables. Potential future work includes dynamically setting the weight factor, reducing it to a value between one and zero in situations where a lower charging power is feasible. For instance, this could be applied when a single aircraft has a lot of available power capacity and remaining time for charging. Another candidate for future research is improving model accuracy. Currently, losses due to inefficiencies in power electronics and variations between different airport power system topologies discussed in Chapter 2, are not considered in the optimization framework. Improvements in this area could be inspired by sources such as [15]. Over time, it will also become necessary to implement a real-world charging power controller to validate the simulations.

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10 Copyright Statement

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13 Appendix

A Convex quadratic programming

Quadratic programming (QP) addresses the optimization of quadratic functions under linear constraints. Specifically, it involves optimizing (either minimizing or maximizing) a multivariate quadratic function subject to linear constraints on the variables. Formally, a QP problem can be expressed as:

$$Min \quad c'x + \frac{1}{2}x'Qx$$
$$Subject\ to \quad Ax \leq b$$

For a QP problem to be convex, the matrix Q must be positive semidefinite, meaning that all its eigenvalues are non-negative. This ensures that the optimization yields a globally optimal solution, avoiding local optima. In the case of a diagonal matrix Q, the QP problem is convex if all the diagonal elements of are positive.

Consider the following specialized QP problem:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \qquad Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}, \qquad c = 1000 \cdot \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$$

Subject to the constraints:

$$-1000 \leq x_1 \leq 1000$$
$$-1000 \leq x_2 \leq 1000$$
$$x_1 + x_2 \leq 1500$$
$$x_1 + x_2 \geq -1500$$

Table 7 presents solutions for different values of q and w. The table illustrate how changes in w_1 and w_2 affect the solution, reflecting the prioritization imposed by the weights and the constraints of the problem.

Table 7 – Example solutions

q	w	x_1, x_2	Comment
[0.5;0.5]	-1	[-750,-750]	Lower bound of sum restricts the values.
[0.7;0.3]	-1	[-1000,-500]	Lower bound restricts values, with higher prioritization on x_1.
[0.7;0.3]	0	[0,0]	Zero values.
[0.7;0.3]	0.1	[333,142]	Small weight results in smaller x values.
[0.9;0.1]	0.1	[999,111]	Small weight gives small x, much higher prioritization on x_1.

B BESS modelling

The power flow to or from the battery energy storage system (BESS) is expressed as:

$$P_{bess} = \begin{cases} P_{bess\ avail}, & if\ P_{bess\ avail} < 0 \\ min\ (P_{bess\ avail}, P_{charge\ bess\ max}), & else \end{cases}$$

Here, $P_{bess\ avail}$ represents the power available from the BESS, given by:

$$P_{bess\ avail} = PC_{grid} - P_{airport} - P_{aircraft}$$

The power $P_{bess\ avail}$ becomes negative if the total power required for charging the aircraft ($P_{aircraft}$) exceeds the installed power capacity from the electricity grid (PC_{grid}) minus the airport power consumption ($P_{airport}$).

The charging power is required to be zero once the target State-of-Charge (SOC) is reached. This logic is handled by $P_{charge\ bess\ max}$, defined as:

$$P_{charge\ bess\ max} = \begin{cases} PC_{bess\ max}, & if\ SOC_{bess} < SOC_{bess\ tar} \\ 0, & else \end{cases}$$

The BESS power capacity is assumed the SoC-dependent. This is represented by:

$$PC_{bess\ max} = k_{Max}(SOC_{bess}) \cdot PC_{bess}$$
$$PC_{bess\ min} = k_{Min}(SOC_{bess}) \cdot (-PC_{bess})$$

where k_{max} and k_{min} are defined schematically in Figure 9. This modeling implies that as the BESS approaches a depleted state, the power capacity available for charging the aircraft will approach zero.

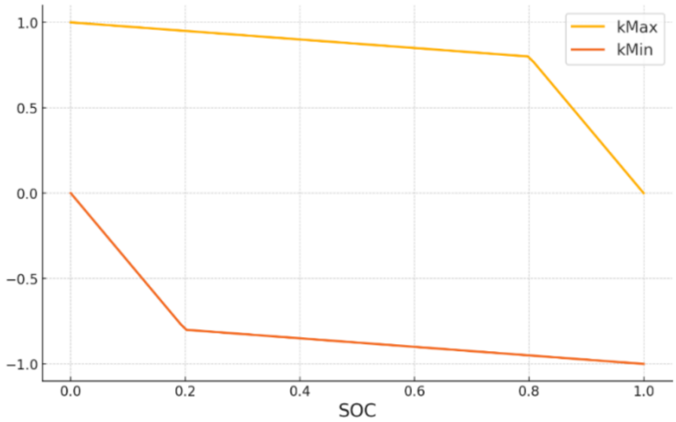

Figure 9 – Normalized BESS power capacity as a function of SOC.

The SOC of the BESS, SOC_{bess}, is updated according to the equation:

$$SOC_{bess} \leftarrow SOC_{bess} + \frac{P_{bess}}{E_{bess}} \cdot dt$$

The causality in this process is such that $P_{aircraft}$ is calculated prior to the SOC update. Consequently, the updating of the SOC_{bess} implicitly depends on its power capacity. In other words, if the SOC is low, the available power for charging the aircraft is limited.