FT2025
SWEDISH AEROSPACE AT THE CROSSROADS
The 12th Swedish Aerospace Technology Congress
FT2025 in Stockholm
October 14-15, 2025

Technical concepts of airport infrastructure for charging battery-electric aircraft

Svetla Käck[1], Anton Karlsson[1], David Daniels[1], Magnus Eek[1], Jonny Johansson[2], Harrison John Bhatti[1], Simon Reinberth[3] and John Nilsson[4]

[1] The Swedish National Road and Transport Research Institute, Sweden
E-mail: svetla.kack@vti.se, anton.karlsson@vti.se, magnus.eek@vti.se, david.daniels@vti.se, harrison.john.bhatti@vti.se
[2]Luleå University of Technology, Dept. of Computer Science, Electrical and Space Engineering, Sweden
E-mail: jonny.johansson@ltu.se
[3]Heart Aerospace, Gothenburg, Sweden.
E-mail: simon.reinberth@heartaerospace.com
[4]Swedavia, Stockholm, Sweden
E-mail: john.nilsson@swedavia.se

Abstract

The paper presents results from the research project "Flexible and automated aircraft charging via energy storage at airports" (FAACE), studying how airport infrastructure could be designed to meet the requirements of future aviation and propulsion technologies. The project is limited to focusing on concepts for charging battery-powered electric aircraft. As there are currently major uncertainties regarding the technical, operational and business developments in electric aviation, it is desirable to design for flexibility in the airport infrastructure.

This paper outlines the scope of the problem in terms of airport and aircraft assumptions, and proposes four different technical concept topologies for the charging infrastructure system, where some are presented with several possible variants. Some of the concept topologies explored include mobile or fixed power electronics components, as well as including possible battery storage systems, that can also be stationary or mobile. The mobile technical solutions utilize an automated vehicle that can take charging equipment and / or a battery storage unit close to the aircraft. Furthermore, we propose several evaluation criteria which are used to make a concept comparison, assuming some general characteristics of the aircraft, the airport, and their operation. These include estimates of energy efficiency, load to the electrical grid, flexibility and scalability aspects, land usage, electromagnetic interference aspects and very approximative costs.

The advantages and disadvantages of the different concepts are discussed, and we describe situations when some of these concepts would be found to be most suitable, which depends on the exact criteria prioritization from the airport perspective. The comparison is visualized by providing calculation examples.

Results show that no single concept fits all airport types; fixed infrastructure offers high efficiency but low flexibility, while mobile and hybrid solutions provide adaptability at the cost of complexity and lower efficiency. The suitability of each concept depends strongly on airport size, traffic patterns, and infrastructure priorities.

Keywords: Airport charging infrastructure, electric aircraft charging, mobile energy storage

1 Introduction

Battery-powered electric aviation has a limited but important role in a sustainable transformation of the air transport system, and previous studies show that there could be potential for a new market for regional electric air travel [1].

A large portion of the existing research focuses on aviation and propulsion technology, which is indeed important, but to enable a sustainable transition of aviation a holistic perspective is required where increased focus is directed towards infrastructure issues. An important subset of this concerns the infrastructure at the airports themselves.

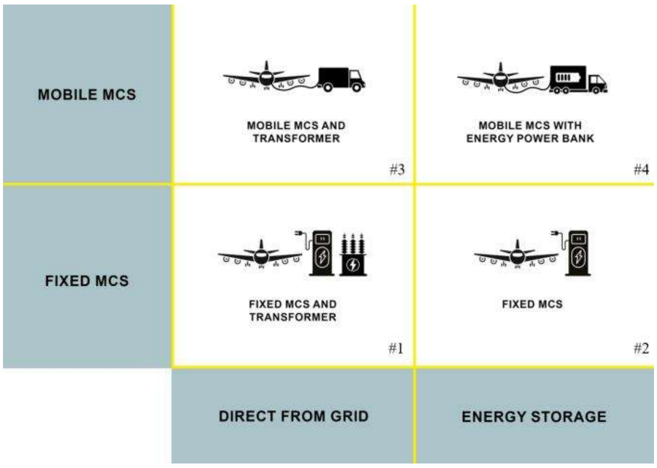

Figure 1. Technical concepts, general description. The numbers of the quadrants connect to the numbering of concepts described in section 3.

The research project *Flexible and automated aircraft charging via energy storage at airports* (FAACE)[1] has been limited to focusing on the identification and evaluation of concepts for charging battery-powered electric aircraft. As there are currently great uncertainties about the technical, operational and business development of electric aircraft, design for flexibility in the airport infrastructure is desirable [2, 3]. The overall aim of the project is to increase the focus of research on airport infrastructure issues for a sustainable transformation of the air transport system, and more specifically investigate new solutions for charging infrastructure that, while solving a task at the airport, can also be an asset in the energy system and thus contribute to new business models for various actors [4].

A specific solution that is studied and compared with more conventional alternatives consists of a mobile automated charging vehicle combined with energy storage. The vehicle's energy storage is either recharged or replaced at a stationary energy storage, whereby transport takes place to the aircraft's parking area where the aircraft is fast charged with a cable from the vehicle. This technical concept is expected to provide flexibility, both in terms of mitigating constraints regarding placement on the airport and by enabling a decoupling between the grid and the power-intensive fast charging of aircraft.

This paper describes the problem space in terms of airport and aircraft assumptions and proposes a number of different technical concept topologies for the charging infrastructure system, where some are presented with several possible variants. Some of the concept topologies explored include mobile or fixed power electronics components, as well as including possible battery storage systems, that can also be stationary or mobile. The mobile technical solutions utilize an automated vehicle that can take charging equipment and/or a battery storage unit close to the aircraft. Further, we suggest several evaluation criteria which are used to make a concept comparison, assuming some general characteristics of the aircraft, the airport, and their operation. These include estimates of energy efficiency, load to the electrical grid, flexibility and scalability aspects, land usage, electromagnetic interference aspects and very approximative costs. Finally, the advantages and disadvantages of the different concepts are discussed, and we describe situations when some of these concepts would be found to be most suitable, which depends on the exact criteria prioritization from the airport perspective. The comparison is visualized by providing calculation examples.

2 Technical background – system definition and general assumptions

This chapter presents the system studied and some general assumptions that frame the technical solutions explored.

The concepts design at an overall level are presented in Figure 1. The system considered incorporates the aircraft, the charging infrastructure needed for charging them, but also includes auxiliaries needed for charging such as extra vehicles and possible energy storage. This system can at the next level be connected to secondary systems at the airport such as other ground vehicle fleets, guest car parking for electrical vehicles, possible energy generation facilities at the airport, etc.

The (primary) system considered here consists of four categories of system components:

- Aircraft and possible complementary cooling equipment: This category includes the electrified aircraft which have their onboard charging equipment with specific charging requirements dependent on the power electronics design, and a preferred charging process. In some cases, the aircraft require an external cooling to be performed during the charging, which means that an extra designated ground vehicle must be involved and connected.
- Ground power electronics equipment: Both fixed and mobile power electronics, such as transformer, converters, cables.
- Battery electric storage systems (BESS): Several alternatives, present in some of the concepts.
- Auxiliary charging vehicle with its own charging station: This vehicle carries mobile parts of the charging infrastructure, present in some of the concepts, the last distance to the aircraft. This vehicle could be an autonomously operated truck.

General charging requirements' assumptions are as follows:

- Commercial aviation needs short turnaround times in order to ensure good cost profile potentials, i.e. typically 35-45 min. This requirement limits the charging possibilities to megawatt charging solutions.

[1] FAACE is funded by The Swedish Transport Administration and is carried out under the leadership of VTI in collaboration with Luleå University of Technology (LTU), Heart Aerospace, Einride and Swedavia.

- Note that the abbreviation MCS in the two-by-two matrix presented in Figure 1, stands for Megawatt Charging System, but not necessarily the standard currently being developed with the same name. No assumptions on the communication protocols are implied in this study. However, based on FAACE workshop discussions, it can be assumed that having the same standard for aircraft and trucks would be good for synergies with other electrical vehicles on site.

- When comparing concepts, it is important to identify the dimensioning cases involved. The specific scenarios considered must include assumptions about the number of aircraft required to be simultaneously charged and at what rates, as well as matching these to the available capacity of the grid. For example, charging rates could be assumed for simplicity to be constant at max rates, or modelled as variables depending on battery characteristics such as state-of-charge, etc. Furthermore, it also might be possible to purposely design for cases with limitations where not all aircraft should be able to charge at the same time at max-rates as such designs can optimize charging infrastructure costs. It is assumed that aircraft arrive with empty batteries and charge to full battery every time.

- The charging requirements also include assumptions for the cases with BESS and vehicles: a sound comparison requires reasonable assumptions on the number of trucks and BESS capacity dimensioning to be specified.

3 Technical concepts – overview

Figure 2 presents the baseline or reference case for all technical concepts. It shows a concept (#1) with a fixed charger charging directly from the grid where each aircraft stand has its own entirely separate designated charger rated for managing the maximum charging capacity. Another approach is to install the converters – physically – closely to the incoming power source whilst making it possible to direct the power where it is required the most, see variant (#1.1). This is achieved by splitting the full rated power by a number of converters rated at lower power – for instance at one fourth of the maximum power one aircraft requires – and switchgear which together makes it possible to direct the power flow [5] [6]. This modular approach might be advantageous since it is unlikely that all stands require the full rated power simultaneously as a typical battery requires a charging power dependent on state of charge due to – for instance – efficiency [7]. In turn this approach might save some power electronics related cost as the full installed power can be lowered compared to concept #1.

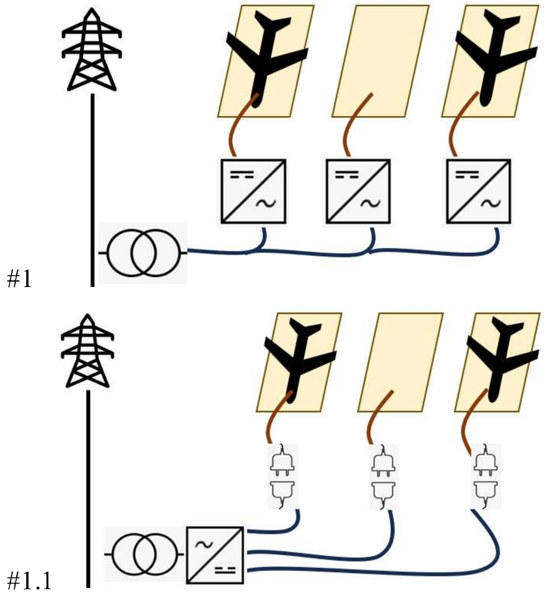

Figure 2. Technical concepts, baseline #1 and variant #1.1, both with a fixed charger charging directly from the grid.

Figure 3 presents concepts where a fixed battery storage system has been added. This makes it possible to charge directly from the grid or from the battery - or perhaps most likely from a combination of both - thereby offering the possibility to optimize load profiles. It is possible to place the battery in different positions electrically, see concept #2 and #2.1. The main advantage of adding a BESS is that it makes it possible to limit the power supplied by the grid at times when high power is in demand. The capacity of the battery can be optimized in several ways, depending on what the dimensioning case is required to be, for instance high energy or high power. Naturally, concepts #1 and #1.1 can also be combined with #2.1, i.e. combing power rate split and battery storage.

The difference between concept #2 and #2.1 is that the BESS is electrically located at the DC-bus in the former and at the AC-bus in the latter. The latter concept is advantageous in terms of controllability of the power and energy at the battery terminals, as it is one converter alone that controls these quantities whereas in concept #2 it is a combination of all converters that makes up the energy and power level at the battery terminals, possibly making it more vulnerable to faults. On the other hand, supplying energy from the BESS to any aircraft requires only one energy conversion in concept #2 whereas in concept #2.1 it requires at least two, lowering the efficiency. h

Figure 4 presents a concept where a part of the charger system is made mobile, in this case the AC to DC converter, i.e. the battery charger. This makes it possible to share the equipment between gates whilst not having to install a significant amount of fixed charging infrastructure at certain stands. However, as shown in Figure 4 it is required to have an AC

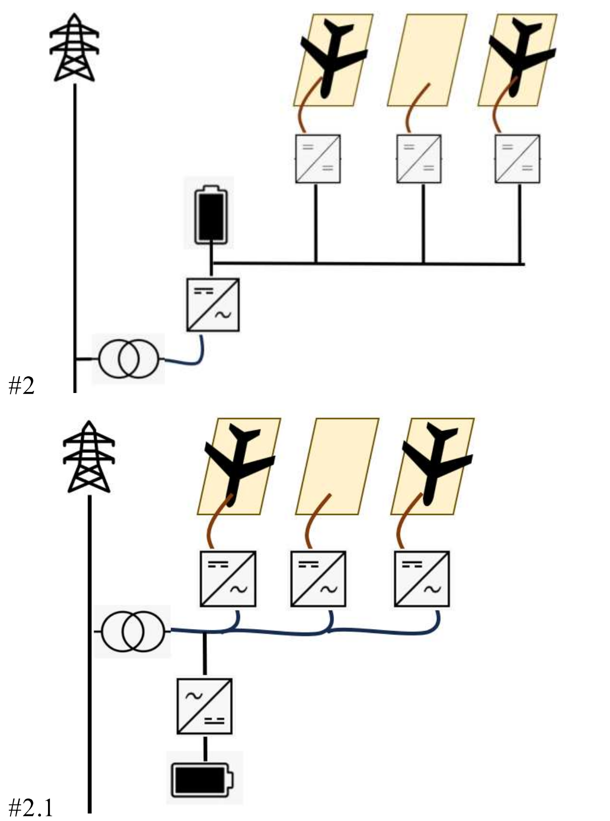

Figure 3. Technical concepts, concept #2 and variant #2.1, fixed charger and utilizing a battery storage unit.

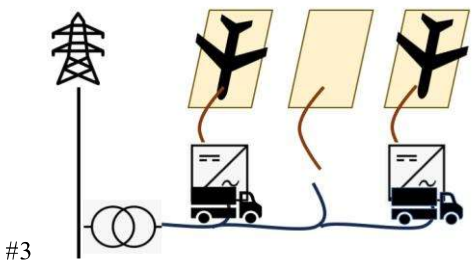

Figure 4. Technical concepts, concept #3, mobile charger.

connection available with supporting the required power level. This approach opens for a higher level of flexibility than the previously presented concepts. Naturally, the number of equipped vehicles depends on the number of electric aircraft requiring charging simultaneously.

Figure 5 shows a design with a mobile battery storage system – concept #4 – and additionally a design which combines concept #4 and concept #2 with a static energy storage system – concept #4.1. In this case it is illustrated as a storage system that is a part of the surrounding infrastructure at an airport, buildings, lighting, charging of road vehicles, etc. Electrically, with regards to connection point, the static energy storage is similar to concept #2. This design is the most flexible of the concepts evaluated in this work in that it does not require any fixed infrastructure at the gates but rather the infrastructure is brought to the aircraft. However, it does

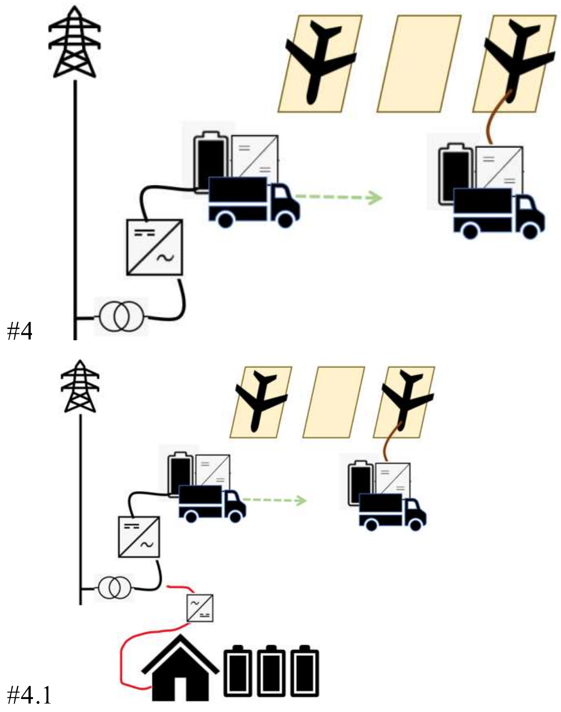

Figure 5. Technical concepts, concept #4 and variant #4.1, fixed charger and utilizing a battery storage unit.

require one vehicle equipped with energy storage and power electronics per number of aircraft charging simultaneously, meaning the cost increases significantly with this number. For an airport with relatively few electric aircraft turnarounds each day (i.e., a small airport, or a larger airport during the early stages of electric aircraft adoption) this approach can still be very attractive. Again, assumptions regarding the number of trucks and ESS capacities must be clearly defined.

3.1 Summary - technical concepts

Four different main concepts illustrating the overall system topology regarding energy transfer to one or several aircraft are presented. Concept #1 illustrate a 'straight forward' topology where the energy is fed to the aircraft from the grid via an AC to DC converter – much like a standard fast charger in the automotive sector. Concept #2 incorporates a battery storage system, facilitating optimization of energy flow from the grid. The subsequent concepts - #3 and #4 - both incorporate a mobile part of the charging system. The former is based on a system where the AC to DC converter is mounted on a mobile platform and brought to the aircraft whereas in the latter a battery storage unit with related electronic equipment is brought to the aircraft. For an airport with the need to charge multiple electric aircraft simultaneously (i.e., a larger airport, later in the electric aviation adoption curve), there is no reason that all of its multiple chargers must be identical. It could be advantageous for an airport to adopt a portfolio of heterogeneous chargers, which collectively minimize capital costs, operating costs, and disruptions to airport operations better than a similar portfolio of identical chargers. Nevertheless, for simplicity, in this study we restrict the analysis to that of a single charger at an airport, in order to limit the number of combinations and more easily compare the different concepts, the number of concepts are limited to four major ones with some additional sub-concepts.

4 Evaluation methodology and criteria

To be able to compare the different technical concepts a number of metrics at different levels of abstraction are proposed.

Quantitative:

- Installed charging power - P_{charge}, for example, number of charging stations x charging power per station.
- Energy efficiency - η, from grid to aircraft not including the losses within the aircraft.
- Energy storage capacity - E_{BESS}.

Semi-quantitative:

- Equipment area required, general estimates.
- Costs, general estimates.

Qualitative:

- Possibility of cutting load peaks via energy storage.
- Flexibility to ramp up and down the aircraft charging capacity at the airport. In extension, also including the ability to move some equipment to other airports.
- Possible participation in extra energy services.
- Electromagnetic compatibility considerations.

Some parts of the installed equipment are deemed required by all the concepts, such as a transformer – which is why this is left out of the comparison. When considering the efficiency of the different concepts, the cable losses are omitted due to the relatively low losses in cabling compared to – for instance – converters and batteries and also that the required cabling is similar between the different concepts.

The technical concepts were evaluated using a combination of component-level and system-level modelling and simulation. Modelica, executed in the OpenModelica environment, was used for detailed modelling and simulation of individual components, such as battery storage units charging strategies. Python was employed for higher-level system modelling, scenario definition, and simulation of operational behaviour across different airport configurations. Python was also used for data processing and results visualization.

4.1 Component Efficiency assumptions

When comparing energy efficiency between different designs, the following component efficiency is assumed:

- AC/DC converters: 95%
- DC/DC converters: 96%
- Battery 'round trip'- efficiency: 93%

'Round-trip' efficiency refers to the energy losses incurred during both charging and discharging cycles. It is a substantial simplification to assign a fixed number to the efficiency of any conversion in this context as the efficiency depends on several parameters, such as load, temperature, state-of-charge, etc. However, the number assigned here are chosen based on literature [8], [9], [10] and are still representative when evaluating the different concepts at the level of detail chosen in this study. As shown in Section 3 some of the concepts incorporate a mobile platform (truck) on which either a converter (charger) or a converter and a battery storage are placed. Naturally, the truck consumes a certain amount of energy. However, the energy consumed by the vehicles is negligible compared to energy fed to the aircraft. One could assume a consumption of approximately 1 kWh/km for the truck and a distance covered in the range of single digit kilometres per aircraft recharged meaning less than 10 kWh consumed by the truck per aircraft which in turn requires in the range of 1 MWh of energy. Moreover, the truck's energy consumption can be scheduled - timing and power draw - so this does not factor into the peak power consumption estimates for either aircraft or airport.

5 Assumptions on aircraft, airports and the charging process

This section covers the technical assumptions relating to the aircraft, charging system and airport.

5.1 Aircraft

In this project, the characteristics of the aircraft are defined as follows:

- The energy required by the aircraft at the airport is 1 MWh. This could be considered a low-end estimate if future aircaft incorporate larger capacity batteries.

- The turnaround time - i.e. the time available for charging - is at most 30 minutes.

- The charging power is dependent on the SOC, see Figure 6, which shows the charging power as a function of the SOC at the level required to transfer 1 MWh in 30 minutes.

These characteristics are in similar range of aircraft such as Heart Aerospace ES-30 which is a hybrid aircraft with 30 passenger capability and approximately 200 km of full electric range [11]. To some extent, an aircraft battery capacity of 1 MWh is also representative to smaller all-electric aircraft. Here it is assumed that every aircraft always takes off with full batteries, and the energy supplied is equal to the consumed energy in the previous flight. This analysis considers therefore the extreme case of needing to charge 1 MWh in 30 minutes, but it is expected that many turnarounds will require less energy than the maximum and could be charged at lower power. This could become important in an analysis of multiple electric aircraft charging simultaneously within a single airport environment, which is beyond the scope of this study.

The derating of the charging power, shown in Figure 6, as the SOC increase is a simplification of reality as the charging profile depends on several factors such as battery temperature, chemistry, etc. It is common to observe a constant - or slightly increasing - charging power below a certain SOC (the increase in power originating from the fact that whilst the current is kept constant, the voltage increases slightly as the SOC increase, hence, the power also increases) and this behaviour is retained in the model used for this work. A maximum charging rate of 3C – and a minimum of 1C – is assumed and the percentage at which the power starts to reduce is chosen so that the battery can be fully charged from 0 to 100% in 30 minutes. A strictly linear reduction of charging power is a simplification as the actual reduction of power in batteries depends on several parameters. However, in order to capture the overall behaviour of aggregated charging power when charging several batteries, the characteristics shown in Figure 6 is deemed an accurate enough representation.

5.2 Airport

Installed power capacity and maximum usage vary depending on the airport size and local characteristics. For our purposes in the analysis, *small*, *medium* and *large* airports are considered which are defined as follows:

Table 1. Airport characteristics, deemed to be the most relevant frame for evaluation of the technical concepts early in the electric aviation adoption curve

Airport	Grid charging capacity available	Number of aircraft charging simultaneously
Small	2 MW	1-2
Medium	5 MW	2-3
Large	15 MW	3-5

The airport size refers both to the maximum load required for charging electric aircraft and the capacity of the airport's grid connection; it is not necessarily the same as the airport's passenger or cargo throughput. The specifics are established among the project partners.

Furthermore, we assume that the number of aircraft charging simultaneously occur twice a day, once in the morning and once in the afternoon.

5.3 Battery electric energy storage, BESS

Similarly to the aircraft battery storage, the BESS is associated with a specific charging power limitation in order to model a more realistic behaviour than a constant charging power would. The overall charging power characteristics is chosen to be similar to the aircraft battery, as shown in Figure 6, but at a lower power level, see Figure 7. Charging the BESS at a lower power reduces heat production, which increases its lifetime and/or reduces its cooling demand, both of which reduce cost.

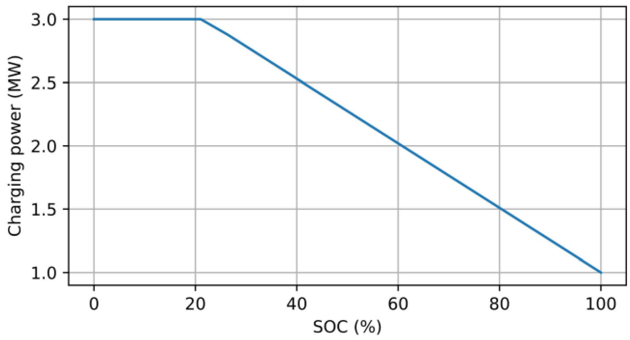

Figure 6. Charing characteristics of the on-board aircraft battery.

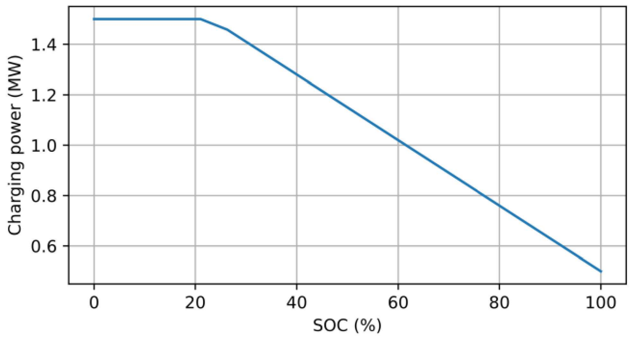

Figure 7. Charging characteristics of the BESS

6 Electromagnetics in the airport environment

The issue of Electromagnetic Interference (EMI) and Compatibility (EMC) in the airport environment has caught attention in recent years due to the deployment of solar cells [12], [13]. These, like many other systems, incorporate switching electronics that may emit radiated EMI that can disturb Communication, Navigation and Surveillance systems (CNS) in the airport environment. Given the severity of this issue, the Swedish Civil Aviation Administration (LFV) has implemented internal guidelines stipulating a protection distance of 3 km between solar cell installations and the nearest CNS system. The EMC concerns extend to other electrical systems incorporating switching electronics, such as motor drive systems and high-voltage battery charging systems, both of which are key technologies in the FAACE project.

The responsibility regarding the airport environment, including the radio environment and EMC, lies with the airport operator. Current regulations include legislation such as the EMC Directive (2014/30/EU), the Electronic Communications Act (2022.482), and the Aviation Ordinance (2010:770); international and national governing documents such as ICAO Annex 10 and Doc 9718 and the Swedish Transport Agency's TSFS 2019:19. The European Commission Regulation 139/2014 outlines requirements and administrative procedures for airports and explicitly mentions activities and land use, which includes sources of non-visible radiation.

One way for the airport to handle the vast array of requirements is to refer to a single standard or set of requirements which the airport has deemed sufficient to secure that all requirements are met. The Swedish national airport operator Swedavia has in their Airport Regulations (AR) referred to emission levels according to EN 61000-6-3 [14] with stricter requirements set for radiated emissions in the radio communication frequency bands of 108- 137 MHz and 380 – 430 MHz [15].

Thus, when new systems are introduced at the airport, it is vital to ensure that these requirements are met. This rises several challenges. One is the fact that system installations are not normally verified against standards and CE marked in the same way that a product is. Secondly, the standards and emission limits allowed for products vary with the type of product [16]. For example, a charger for electric vehicles is subject to the standard EN IEC 61851-21-2 [17], which holds the same radiated emission requirements as EN 61000-6-3. The 61851-21-2 also regulates conducted emissions for the charging system. It does not, however, take the added requirement for radiated emissions in the radio bands as stipulated in the AR into account. An electric vehicle, on the other hand, falls under the standard EN 55012 regarding emissions in the VFH band [18]. The EN 55012 holds a higher emission limit and other means of verification than EN 61000-6-3. Therefore, a vehicle will require special attention in this regard. The sections below in this paper that give the analysis of the proposed charging concepts highlights the specific EMC related challenges that will need to be taken into account for each concept.

7 Comparative analysis of charging infrastructure concepts

In Section 3, the different charging concepts were introduced. Elaborating further on those, below is an analysis of each concept, its characteristics and advantages and disadvantages.

7.1 Technical Concept #1: Fixed charger and charging directly off the grid.

***Concept description**:* One permanently installed charger station for each stand. The cabling can be over or underground.

Advantages: Makes sure that each aircraft has access to its own infrastructure. The highest energy efficiency, in the sense that the losses between the grid and the aircraft are minimized.

Disadvantages: The most inflexible solution (if only one or a few chargers are installed) and requires high installed power.

***EMC considerations**:* The one component with switching electronics is the charging installation itself. Products used in this installation are to be tested according to EN IEC 61851-21-2 regarding conducted as well as radiated emission. The standard holds the same radiated emission baseline as the current Swedavia regulations. The system installation will however need to be verified against the stricter radiated emission limits set in the AR.

Estimated efficiency: As the only present conversion is within the AC/DC converter the losses are created at this point, thus the overall efficiency can be estimated at 95%, see Section 0.

7.2 Technical concept #1.1: Fixed main charger with several outlets, directly off the grid.

***Concept description**:* One permanently installed main charger with several outlets enabling a potentially lower total installed power (in terms of AC/DC converters) compared to concept #1, see Section 3 and 8.1.4 for details.

Advantages: Good utilisation of installed conversion power and saving some power electronics costs. Possibly slightly higher efficiency than concept #1.

Disadvantages: Requires fixed installation. Although it should be a smaller task to expand this concept into more charging stands compared to concept #1.

***EMC considerations**:* Similar to concept #1 with the main difference being that in this concept the cabling feeding switched voltage and current ('after the AC/DC converter') is longer, potentially presenting a higher possibility of coupling emissions into the surroundings.

Estimated efficiency: Only one conversion occurs, thus the efficiency is estimated at 95%. Depending on how the main charger is designed, i.e. how many modules at a certain power level, it is possible that each module can operate at a power level which increase the efficiency slightly. Although, the charger in concept #1 can also be based on the same philosophy; a number of modules at lower power levels rather than one big converter designed for the maximum power level.

7.3 Technical concept #2 & #2.1: Fixed chargers with battery storage

***Concept description**:* Similar to concept #1 with the addition of a battery energy storage system (BESS). The difference between #2 and #2.1 is the (electrical) location of the battery storage, in the former the BESS is connected to the DC-link feeding all the chargers (which in this case are DC/DC converters), in the latter it has its own AC/DC converter, and all the chargers are connected to an AC-link.

Advantages: The BESS enables peak shaving and reduces the requirement on the available grid power while still ensuring high charging rates. To what extent exactly would depend at large on utilisation rate and BESS energy and power capabilities. Theoretically, the battery can be optimised not only for charging aircraft purposes but for the whole of the airport operations.

Disadvantages: The BESS is associated with a significant capital cost. The level of flexibility is on the same level as concepts #1 and #1.1. Potentially low efficiency due to the extra energy conversion.

***EMC considerations**:* The addition of the BESS includes switching components for charging as well as inverters for AC generation, thus it is a potential source of electromagnetic emissions. The BESS does not have its own product standard but can as a device be verified against a generic standard in the EN 61000-6-X series. To maximize the possibility of compatibility with the airport environment, it should be required that the EN 61000-6-3 has been used. Also in this case, the final system installation at the airport will need to be verified towards the AR and the stricter limits for radiated emissions therein.

Estimated efficiency: Since the amount of energy passing through the BESS – which affects the efficiency – depends on the utilization of the system it is in general terms challenging to associate *one* number with the efficiency. However, it is possible to establish a worst- and best-case scenario regarding the efficiency. Best case scenario, considering concept #2, is when no energy is converted in the BESS, resulting in an efficiency according to:

$$\eta_{\#2,max} = \eta_{AC/DC} \cdot \eta_{DC/DC} = 0.95 \cdot 0.96 \approx 0.91 \quad (1)$$

However, if it is assumed that all energy supplied by the grid is firstly supplied to the BESS which in turn supplies the energy to the aircraft, the final efficiency becomes:

$$\eta_{\#2,min} = \eta_{AC/DC} \cdot \eta_{DC/DC} \cdot \eta_{BESS} = 0.95 \cdot 0.96 \cdot 0.93 \approx 0.85 \quad (2)$$

When considering concept #2.1, a similar behaviour can be concluded:

$$\eta_{\#2.1,max} = \eta_{AC/DC} = 0.95 \quad (4)$$

$$\eta_{\#2.1,min} = \eta_{AC/DC}{}^3 \cdot \eta_{BESS} = 0.95^3 \cdot 0.93 \approx 0.79 \quad (5)$$

Although Concept #2.1 presents a higher maximum efficiency and a lower minimum efficiency compared to Concept #2 - due to fewer conversion stages in the best-case scenario and more conversions in the worst-case scenario - it introduces greater variability in performance. It is worth noting - as previously discussed in Section 3 - that the BESS in Concept #2 likely requires a dedicated DC/DC converter to enable independent control of voltage and current at the BESS, rather than relying on the behaviour of all converters connected to the DC bus.

7.4 Technical concept #3: Mobile charger, directly off the grid

Concept description*:* This concept is electrically similar to Concept #1, in which energy is supplied to the aircraft directly from the grid via an AC/DC converter. However, unlike Concept #1, the AC/DC converter in this case is not a fixed installation; instead, it is mounted on a suitable vehicle that transports the charger to the aircraft. Regarding fixed infrastructure, each charging location must be equipped with an AC outlet rated for the full charging power.

Advantages: Requires less fixed installation. Enables a level of flexibility. High efficiency.

Disadvantages: While offering increased flexibility, this concept introduces operational complexity due to the need for mobile units and coordination. It also combines fixed and mobile infrastructure, which may lead to higher maintenance and logistical challenges without significantly reducing grid dependency.

EMC considerations: This concept adds the transport vehicle, which from an emission point should be certified according to EN 55012. This standard allows higher emission limits than the generic 61000-6-3. Therefore, it is imperative that the vehicle emissions are well understood and verified towards the AR, both in the design and construction phase as well as after system completion.

Estimated efficiency: From an electrical standpoint, this concept mirrors concept #1, yielding an expected efficiency of 95%.

7.5 Technical concept #4 & #4.1: Mobile charger and energy storage

Concept description*:* The energy supplied to the aircraft is initially stored in a mobile BESS unit, which is subsequently delivered to the aircraft. It is also possible to complement the mobile energy storage with a fixed storage unit as well (#4.1).

Advantages: Owing to the minimal fixed infrastructure required near the aircraft, this concept offers the greatest operational flexibility.

Disadvantages: This concept exhibits comparatively low efficiency, as all energy must pass through the BESS. Additionally, the number of aircraft that can be charged simultaneously is limited by the number of available BESS units, which represents a significant cost factor.

EMC considerations: This concept requires an understanding of the emission performance and device level standards of all system parts; the charger, the BESS and the vehicle, as discussed for the previous concepts. A final verification towards the AR is vital and should be performed with the system in all relevant operational modes.

Estimated efficiency: As the total amount of energy finally supplied to the aircraft must circulate BESS, the efficiency becomes identical to the worst case of concept #2.1, i.e. 0.787. The energy usage of the vehicle(s) transporting the BESS to the aircraft is not accounted for considering the efficiency of this concept.

8 Operational evaluation of charging concepts

The first analysis considered a relatively few electric aircraft landings per day, see Table 1. Airport characteristics; a regime in which maximum power draw for aircraft charging is expected to dominate operating costs, and that this might correspond to a situation that airports - of all sizes - might be expected to face as electric flight begins to become adopted. Then, the second case considers a case further down the electric flight adoption curve, in which a majority of flights can be expected to be electric. Therefore a in this section a real-world arrival and departure schedule for domestic flights at a representative Swedish airport is used to stress-test the different concepts, aiming to reveal critical operational characteristics.

8.1 Case study 1 – Charging requirements at airports of varying sizes

Considering Figure 6 and the number of simultaneously charging aircraft it is possible to deduce the required power from the grid, which is shown to be, in many cases, a limiting factor.

8.1.1 Small airport

The small airport is expected to be able to accommodate 1-2 simultaneously charging aircraft whilst expected to have 2 MW of available power. Given the charging characteristics shown in Figure 6, the maximum charging power might reach a maximum of 6 MW, depending on the arrival of the two aircraft.

Concept #1 & #1.1: It is obvious that these concepts cannot meet the requirements of the charging aircraft as the energy is taken from the grid directly. Should one consider only one charging aircraft at once, with the charging power limited to 2 MW, the charging time – assuming 1 MWh of transferred energy – becomes approximately 35 minutes. Charging of two aircraft simultaneously take 60 minutes. The difference in performance between concepts #1 and #1.1 only becomes prominent if the arrival times of the aircraft are shifted, this is not investigated here as the worst-case scenario is considered.

Concept #2 & #2.1: These concepts' ability to accommodate 1-2 aircraft charging is highly dependent on the specifics of the BESS. Assuming one BESS with matching *discharge* characteristics to the *charge* characteristics of the battery in *one* aircraft, it is clear that one aircraft can be supplied by the BESS whilst the other (again assuming 2 simultaneously charging aircraft) is supplied by the grid at the same power level as described by Concept #1 & #1.1. This means that it is possible for one aircraft to achieve a turnaround time of 30 minutes, whereas the other is increased to 37.5 minutes. However, if the BESS has higher *power* capacity than what one aircraft requires, i.e. instead of 3 MW the power capacity is increased to 4 MW, it is possible to achieve the required turn-around time for two aircraft without increasing the energy capacity of the BESS.

Concept #3: Electrically identical to Concept #1. Naturally, two vehicles carrying an AC/DC converter each are required to charge two aircraft. Since the charging power is limited by the grid, the turnaround time is not fulfilled.

Concept #4 & #4.1: Two vehicles are required to charge two aircraft, each equipped with a BESS capable of delivering 1 MWh in 30 minutes. This means that this concept carries the highest amount of external energy storage. However, as stated previously, the amount of fixed infrastructure around the aircraft is limited and the behaviour of transferring energy to the aircraft is similar to the way of refuelling a conventional aircraft. Another consequence of considering this concept is that given enough time between the waves of aircraft arriving, the load on the grid can be significantly reduced as the BESSs can be charged in a queuing manner.

8.1.2 Medium airport

Due to the linear behaviour, the difference between medium and small airport is reduced to required charging power, number of vehicles with charging equipment, etc. The reasoning follows the same logic as in small airport.

Concept #1 & #1.1: At 3 aircraft charging simultaneously, the required power peak at 9 MW which is less than what is assumed to be available. With 5 MW available whilst the aircraft share the available power equally, the total charging time for 3 aircraft become approximately 39 minutes.

Concept #2 & #2.1: With the addition of a BESS, the charging time can be decreased and/or the load on the grid can also decreases. To be able to achieve the specified turn-around time with 5 MW of grid power a BESS with an energy capacity of approximately 750 kWh and a power capacity of approximately 4 MW. Considering conventional BESS's this specification is likely difficult to fulfil. A likely discharge rate is around 1-3 MW which leads to an energy capacity of 1.2-4 MWh.

Concept #3: Electrically identical to Concepts #1 & #1.1. Three vehicles with charging equipment are required. Turnaround time not fulfilled.

Concept #4 & #4.1: Three vehicles with BESS and electronics are required. As the number of vehicles and Battery Energy Storage Systems (BESSs) increases, the likelihood of multiple BESSs requiring simultaneous charging also rises. Consequently, the initial reduction in power demand from the grid is not maintained at the same level.

8.1.3 Large airport

The large airport is assumed to have up to 15 MW of grid power available whilst it should be able to accommodate up to 5 simultaneously charging aircraft.

Concept #1 & #1.1: In this case, the available grid power is enough to accommodate 5 simultaneously charging aircraft.

Concept #2 & #2.1: As stated, the available grid power is enough to fulfil the requirement of 5 aircraft. However, there are additional factors that may justify the integration of a Battery Energy Storage System (BESS) into the charging infrastructure, such as enabling peak shaving and providing the flexibility to draw energy from the grid at economically optimal times based on tariff structures.

Concept #3: Electrically identical to Concepts #1 & #1.1. Five vehicles with charging equipment are required.

Concept #4 & #4.1: Five vehicles with BESS and electronics are required.

Table 2. Summary of the different technical concepts' ability to fulfil the turn-around time.
Legend: ■ = Meets 30 min turnaround | ■ = Does not meet 30 min turnaround

Concept	Key requirement	Small airport (2 MW, 2 aircraft)	Medium airport (5 MW, 3 aircraft)	Large airport (15 MW, 5 aircraft)

#1 – Fixed charger per slot	Grid power only	60 min turnaround (limited power)	39 min turnaround	Meets 30 min requirement
#2 / #2.1 – Fixed + BESS	Grid + stationary storage	One BESS (≥4 MW / 1 MWh)[2]	One BESS (≥4 MW / 750 kWh)	Grid power sufficient; BESS optional
#3 – Mobile charger	Grid power + mobile chargers	2 vehicles needed	3 vehicles	5 vehicles
#4 – Mobile BESS	Mobile storage + chargers	2 vehicles with 1 MWh BESS each	3 vehicles with 1 MWh BESS each	5 vehicles with 1 MWh BESS each

8.1.4 Summary

Table 2 shows the technical concepts, the differently sized airports and what is technically required to fulfil the turn-around time. It is important to note that although allowing a level of flexibility concepts #3 and #4 – especially the latter – are associated with a significant cost increase as the required number of simultaneously charging aircraft increase.

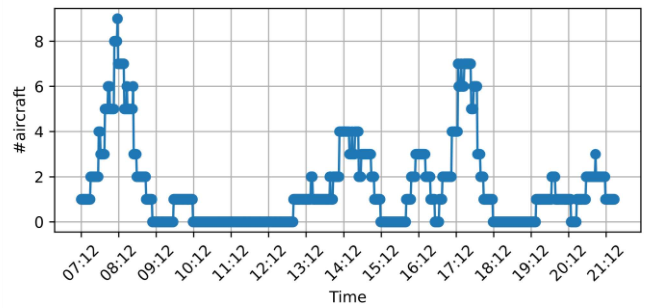

Figure 8. Number of aircraft on ground during a representative day at a domestic airport in Sweden. Note that it is assumed that the aircraft departing the first 30 minutes are charged during the night.

8.2 Case study 2 – High-density electric aircraft operations

In order to evaluate the technical concepts from a possibly future scenario, this section presents a departure schedule of a representative day from a domestic airport in Sweden. As previously, a turn-around time of 30 minutes is assumed, which makes it possible to estimate how many aircraft are on ground, charging, at any given time during the day. The number of aircraft on-ground as a function of time is shown in Figure 8 where the aircraft departing in the first 30 minutes are assumed to have charged over night at the current airport.

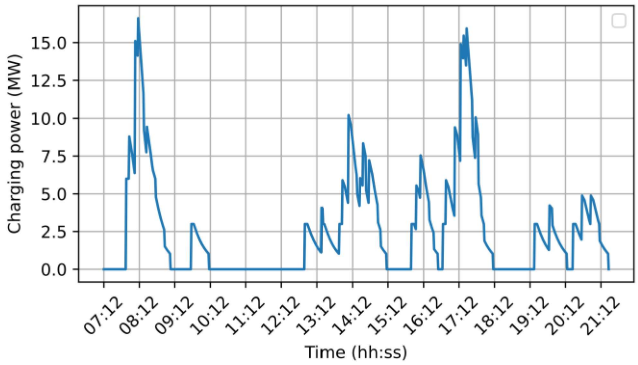

Figure 9. Charging power by minute.

Concept #1 & #1.1: Charging directly from the grid generates a power demand as shown in Figure 9. The power demand curve illustrates clearly that the total power requirement is significantly lower than the maximum power per aircraft (3 MW) times the maximum number of simultaneously charging aircraft (7 units). This is due to the de-rating of charging power as the SOC increase. This also illustrates that concept #1.1 is able to fulfil the charging requirement with an installed power level of approximately 16-17 MW whereas if concept #1 is considered, a total of 21 MW of installed power would be required.

Concept #2 & #2.1: In this case, no distinction has been made between concept #2 and #2.1 as the functionality considering energy management is very similar between the two. Here it is investigated what capacity of the BESS is required to fulfil the charging requirements of the day, shown in Figure 9. To reduce the degrees of freedom, it is assumed that the grid is limited to 1C of the BESS. By iteration it is found that the minimum capacity of the BESS is 4.5 MWh and at this capacity, the chosen day does result in almost two full cycles of the BESS, see Figure 10. It is likely that - should this level of charging power be made available by BESS – a higher capacity is chosen so that the cycling of the BESS is not as

[2] A BESS at this level of C-rate (discharge) is typically significantly higher than currently available systems which usually have a discharge C-rate between 0.5-1C [19] [20] [21]

deep.

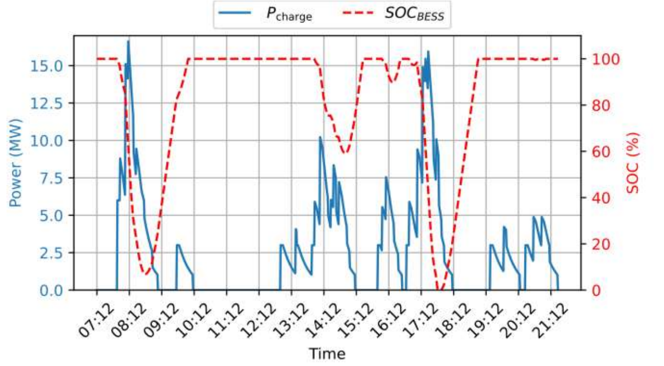

Figure 10. Charging power and SOC of the static battery energy storage.

Concept #3: Electrically identical to concept #1 (not #1.1 in this case) which means a total of 7 vehicles – as per *Figure 8* – with 3 MW of charging capacity each.

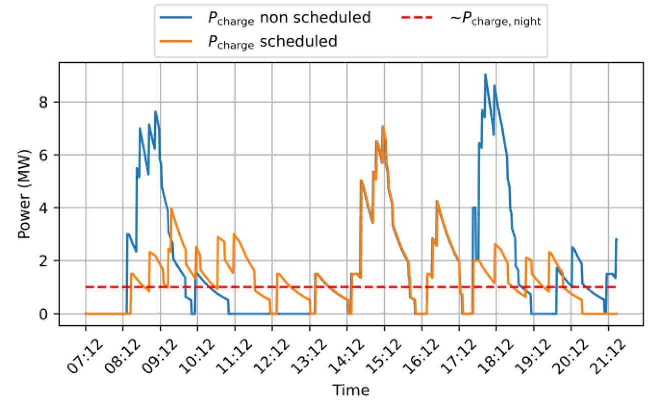

Figure 11. Grid power when charging the BESSs of concept #4.

Concept #4 & #4.1: As in the previous concept, 7 vehicles are required with 3 MW of charging capacity and 1 MWh of transferable energy. Here two different approaches to charging of the BESSs are investigated; one where the BESS is charged immediately after it has served an aircraft and one where the longer periods of time with no or few aircraft present the time is utilized more structurally, i.e. the BESSs are charged as sequentially as possible. Note though that no mathematical optimisation is performed in order to minimise the grid power, the scheduling is rather done 'by eye' in order to make a quick attempt to evaluate the potential of scheduled charging. The result is shown in Figure 11 where the major power peak around 18:00 can be significantly reduced by charging the BESSs overnight instead of immediately after the aircraft have been served. It also shows that when there is a limited amount of time between two peaks in occupancy, between approximately 15:00 and 16:00, the scheduled charging does not lower the amount of power supplied by the grid. During this example day 7 ESSs carrying 1 MWh of useable energy is not enough to supply all aircraft, during the highest occupancy – around 17:00 – either another vehicle or one of the BESSs at approximately double the capacity is required.

With this number of mobile BESSs – being realistic or not – it is clear that in order to relieve stress from the grid the time between peaks in aircraft occupancy is required to be large enough so that charging of the BESSs can be done sequentially rather than simultaneously. This illustrates one issue with this concept as the number of BESSs increase, the challenges of charging several aircraft simultaneously, is instead shifted to charging the BESSs. Implying that this concept is likely most suited for early adoption as it brings several positive aspects when considering flexibility.

8.2.1 Summary

The evaluation of a high-density day at a representative domestic airport demonstrates how varying charging infrastructure concepts handle continuous, time-sensitive demand. Fixed-grid concepts (#1 and #1.1) show predictable but inflexible behaviour, requiring high installed capacity. Concept #1.1, with shared electronics, reduces peak demand through load balancing, highlighting the advantage of modularity. Concepts involving battery energy storage (#2 and #2.1) effectively smooth grid demand but require careful sizing to avoid deep cycling and performance loss. Mobile solutions (#3 and #4) provide valuable flexibility, particularly in dynamic or constrained environments. However, their operational feasibility is tightly linked to coordinated vehicle scheduling and battery charging strategies. In particular, concept #4 benefits significantly from staggered charging of mobile BESS units, demonstrating the potential to reduce grid stress—though this shifts complexity toward scheduling and fleet management. Overall, this scenario illustrates that as electric aircraft traffic intensifies, concepts combining flexibility with smart energy and logistics management will be most effective.

9 Conclusions

This study compared four technical concepts for battery-electric aircraft charging infrastructure, focusing on flexibility, efficiency, scalability, and operational feasibility. No single solution fits all airport contexts; the optimal choice depends on factors such as grid capacity, traffic density, and electrification goals. Fixed infrastructure concepts (#1 and #1.1) offer for instance high efficiency and operational simplicity but require significant grid capacity and lack adaptability. Concepts with stationary battery storage (#2 and #2.1) support peak shaving and grid optimization, though they introduce complexity and reduce efficiency.nMobile solutions (#3 and #4) provide greater flexibility, especially for smaller or early-stage airports, but come with higher costs and lower efficiency due to additional energy conversions. They also raise electromagnetic compatibility challenges that must be addressed for safe integration.nIn summary, a flexible and modular approach will be essential for future-proof airport infrastructure. Ongoing work includes a planned demonstrator project focused on mobile energy storage, which would help validate these concepts under real-world conditions and guide future investments.ll

10 References

[1] J. Salomonsson and J. Hammes, "Det kommersiella elflyget - verklighet eller dröm? En litteraturstudie över elflygets utsikter (VTI Rapport 1029)," VTI, Linköping, 2020.

[2] Clean Aviation, "Clean Aviation," 2025. [Online]. Available: https://www.clean-aviation.eu/.

[3] Fly Zero, "Destination Zero - The technology journey to 2050," 2022. [Online]. Available: https://www.ati.org.uk/wp-content/uploads/2022/04/ATI-Tech-Strategy-2022-Destination-Zero.pdf .

[4] D. Daniels and M. Eek, "The airport as an energy hub (VTI Report 1201A)," VTI, Linköping, 2024.

[5] S. S. G. Acharige, M. E. Haque, M. T. Arif, N. Hosseinzadeh, K. N. Hasan and A. M. T. Oo, "Review of Electric Vehicle Charging Technologies, Standards, Architectures, and Converter Configurations," *IEEE Access,* vol. 11, 2023.

[6] M. Elkeiy, Y. Abdelaziz, M. Hamad, A. Abdel-Khalik and M. Abdelrahem, "Multiport DC-DC Converter with Differential Power Processing for Fast EV Charging Stations," *Sustainability ,* vol. 15, 2023.

[7] S. Xiaojia, S. Bingxiang, W. Jinyu, R. Haijun, Z. Weige and Y. Bao, "Experimental study on charging energy efficiency of lithium-ion battery under different charging stress," *Journal of Energy Storage,* vol. 68, 2023.

[8] K. Zhou, Y. Wu, X. Wu, Y. Sun, D. Teng and Y. Liu, "Research and Development Review of Power Converter Topologies and Control Technology for Electric Vehicle Fast-Charging Systems," *Electronics ,* vol. 12, 2023.

[9] S. Piasecki, J. Zaleski, M. Jasinski, S. Bachman and M. Turzyński, "Analysis of AC/DC/DC Converter Modules for Direct Current Fast-Charging Applications," *Energies ,* vol. 14, 2021.

[10] M. Safoutin, J. Cherry, J. McDonald and S. Lee, "Effect of Current and SOC on Round-Trip Energy Efficiency of a Lithium-Iron Phosphate (LiFePO4) Battery Pack," *SAE Technical Paper,* 2015.

[11] H. Aerospace, "Introducing the ES-30," 2025. [Online]. Available: https://heartaerospace.com/es-30/. [Accessed 22 05 2025].

[12] M. Kane, N. Taylor and D. Månsson, "Electromagnetic Interference from Solar Photovoltaic Systems: A Review," *Electronics ,* vol. 14, 2025.

[13] Försvarsmakten; Elsäkerhetsverket; Totalförsvarets Forskningsinstitut (FOI) ; Fortifikationsverket; Försvarets Materielverk (FMV) ; Försvarets Radioanstalt (FRA); SEK Svensk Elstandard, "Utredning av elektromagnetiska störningars försvårande för totalförsvarets intressen eller anläggningar," Högkvarteret, Stockholm, 2020.

[14] IEC 61000-6-3:2020., *"Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for equipment in residential environments"*..

[15] Swedavia, "Airport Regulations Stockholm Arlanda Airport," [Online]. Available: https://www.swedavia.net/airport/arlanda/airportregulations/ar/Airport_Regulations_ARN_ENG.pdf. [Accessed 24 05 2025].

[16] J. Johansson and T. Salm, "Airport electrification and electromagnetic emissions – standards and challenges"," in *To be published at the 12th Swedish Aerospace Congress, FT2025*, Stockholm, 2025.

[17] IEC 61851-21-2:2018, *Electric vehicle conductive charging system - Part 21-2: Electric vehicle requirements for conductive connection to an AC/DC supply - EMC requirements for off board electric vehicle charging systems.*

[18] EN 55012:2007, *Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of off-board receivers.*

[19] GTCAP, "GTEF-1024V 500KWH/250KW-C Capmega High Voltage ESS," 2025. [Online]. Available: https://www.greenteche.com/gtef-1024v500kwh-250kw-c-capmega-high-voltage-ess.html?. [Accessed 23 05 2025].

[20] evesco, "ES-10001000NA Technical specification," 2025. [Online]. Available: https://www.power-sonic.com/wp-content/uploads/2022/03/ES-10001000NA-1000kW-1000kWh-containerized-BESS.pdf. [Accessed 23 05 2025].

[21] Volvo Energy, "Battery Energy Storage System - BESS," 2025. [Online]. Available: https://www.volvoenergy.com/en/energy-storage.html. [Accessed 23 05 2025].