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Transportation Goes Electric – Exploring the Potential of Smart Charging Strategies for Airports

Hampus Alfredsson[1], Patrik Ollas[1], Sara Ghaem Sigarchian[1], Christoffer Aalhuizen[2], Jennifer Leijon[2], Karin Thomas[2]

[1]*(corresponding author) RISE Research Institutes of Sweden, Lindholmspiren 7A, Gothenburg, Sweden,* hampus.alfredsson@ri.se

[2]*Division of Electricity, Department of Electrical Engineering, Uppsala University, Lägerhyddsvägen 1, Ångström Laboratory, Uppsala, Sweden*

Executive Summary

Transport electrification continuously increases globally and propagates to new, even-larger vehicle applications due to decreased costs, battery technology improvements, and charging infrastructure rollout. This work highlights the importance of strategic planning for large electric vehicle charging nodes, like depots, terminals, airports and ports. Specifically from the perspective of predicting future power requirements and how to satisfy energy demand using a combination of smart charging algorithms, local photovoltaic electricity production and battery energy storage systems. A case study is presented where developed tools and models are applied to an airport for high-power charging of future electric aircraft.

Keywords: power management, smart charging, energy storage, photovoltaic, modeling

1 Introduction

For an increasing number of transport applications, all-electric solutions are becoming a relevant option. For instance, in 2021, the global electric bus stock was 670 000 vehicles (4% of the global fleet), and the electric heavy-duty truck was at 66 000 (0.1% of the global fleet) [1]. By 2035, forecasts expect most new trucks to be electric in the US, EU and China [2]. The European Commission recently proposed far-reaching targets to amend the EU's CO_2 standards for trucks, trailers and buses, requiring, for instance, most new trucks to cut their emissions by 45% in 2030, 65% in 2035, and 90% in 2040 [3]. Furthermore, studies and reports now analyze the future potential for introducing regional electric aircraft [4] and interregional electric container shipping [5], to mention a few. However, enabling an electrification transition is not only a question of vehicle technology development. Building out adequate power supply infrastructure needs to happen in parallel, or even proactively, to reassure people and transport operators that the transition is supported by a reliable and accessible infrastructure system. Most likely, this must be a shared responsibility between the public and private sectors in terms of making the necessary investments and choosing the appropriate type of charging solutions.

The underlying work presented in this paper explore potential challenges and possible solutions at larger nodes for stationary charging. All stationary charging locations handle vehicle arrivals and departures at different times during the day with various energy and power demands. What power capacity to install at a specific site should be highly important, as it affects the attractiveness for transport operators to utilize the site (resulting in better economy of the charging infrastructure), and to make appropriate investments in charging equipment, grid connections, and other components. Connecting a site to higher power capacity means higher investment costs, and depending on the surrounding electricity grid there might also be limitations for what is possible to provide. Furthermore, as peak power costs (tariffs) are becoming more common in electricity pricing models (in Sweden all power grid companies must have adopted power tariffs by 2027 [6]), it is of interest to avoid high power imports from the grid when possible.

In this paper, the aim is to provide an analysis of possible solutions to reduce peak-power import from the electricity grid and load balancing of the aggregated charging. This includes the implementation of smart-charging algorithms as well as on-site electricity production and energy storage. Meaning, on one hand, direct power reduction measures by controlling charging levels and distributing power supply in time. And on the other, solving the power supply issue by using alternative sources to the electricity grid.

2 Methodology

The methodology presented in this paper constitutes of two key pillars; (i) understanding the energy demand and power distribution for a large charging node, and (ii) developing an analysis tool and control strategies for charging and power supply solutions to meet the demand with minimal grid load. The two pillars are closely connected since more information about demand and distribution improves the possibilities for strategic supply planning. For instance, at a public parking space for EVs, it might be difficult to know exactly when charging is requested (assuming no booking system is in place). This means that the power supply will either have to be installed for maximum possible occupancy and charging demand, or with use of some power management system working in real-time; making predictions of future demand patterns based on historical data. Infrastructure and power supply might not be a big (or costly) issue for smaller sites with few daily visitors in the lighter vehicle categories. However, for larger sites, or sites where visiting vehicles have large batteries and need high-power charging, the challenge quickly becomes more significant. Conversely, commercial fleets including e.g. buses, trucks, ferries or aircraft often rely on some predetermined schedule in time and space, meaning that the charging infrastructure can more easily be tailored to equal demand.

As a representation of a larger charging node, this paper focuses on the case of an airport where a scheduled fleet of battery-electric aircraft relies on charging. Necessary simulation models and feasible future scenarios have been developed. A reference case is derived for the aircraft charging, followed by analysis of several energy and power supply system configurations in terms of potential to meet the demand and economical feasibility. Models used are generic and not specially adapted to airports; hence they can be applied to any charging node in continued studies given input data and information about vehicle fleets and site-specific prerequisites. In-house modelling has been conducted using Python, though other commercial tools have been used to simulate for instance on-site electricity production.

2.1 Aircraft charging demand modeling

The charging demand modeling is exemplified by the airport of Visby. Situated on the island of Gotland, Sweden (57°38'27.2"N, 18°17'45.67"E). Visby Airport is currently preparing to accept battery-electric aviation when commercially available [7], and several routes have been identified as potentially feasible for electric aviation [8]. Introducing electric aircraft operations might lead to increased power capacity requirements at an airport due to high-power charging during short turnaround times, which is why this is an interesting case to study. Using tools and methods developed in a previous work by the authors [9], a future scenario is defined as constituting six regional electric aviation connections, followed by flight simulations and scheduling. Each connection is within a range of approximately 200 km, shown in Figure 1, including the airports; Visby Airport (ESSV), Stockholm Bromma Airport (ESSB), Stockholm Skavsta Airport (ESKN), Norrköping-Kungsängen Airport (ESSP), Linköping/SAAB Airport (ESSL), Västervik Airport (ESSW) and Kalmar Airport (ESMQ). Limiting the distance to 200 km is considered feasible, at least initially for electric aircraft, based on the current battery technology [4].

A daily flight schedule is developed for 16 fligths in each direction with Visby Airport as a regional hub. The distribution of flights is designed as a commuter-schedule with primarily morning and afternoon flights as seen in Figure 2. The aircraft type used to simulate flight missions and resulting energy consumption is a 19-seat battery-electric model, parameterized according with certification level CS/FAR-23 (19 seats and maximum take-off weight of 8,618 kg) [10]. A battery size of approximately 800 kWh is set for each of the aircraft.

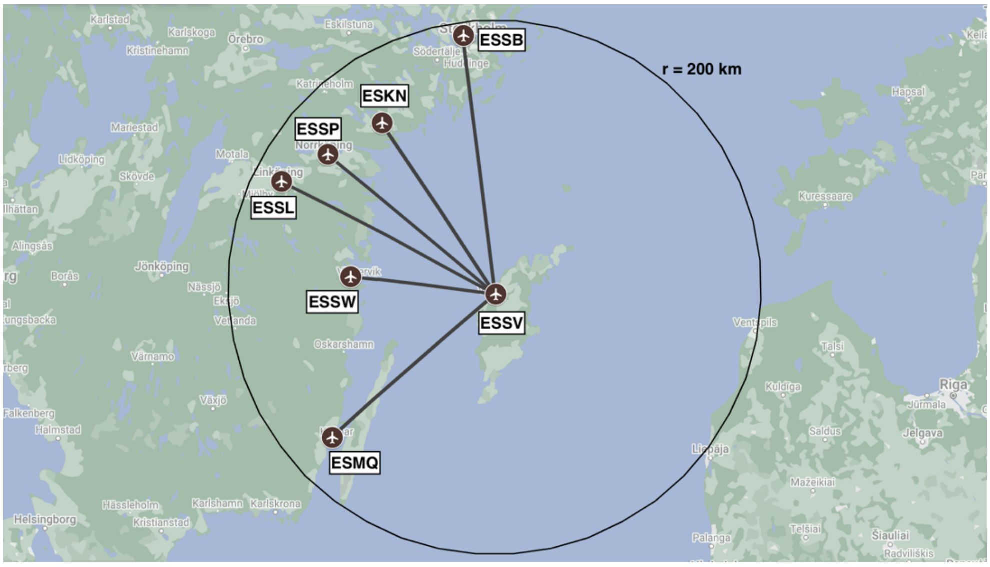

Figure 1: Identified possible electric flight connections within 200 km radius with Visby Airport as a regional hub.

The schedule in Figure 2 is produced using a timetable optimization model with the objective to fulfil a desired daily flight demand (expressed as number of flights per connection, distributed over user-specified time intervals) with the minimum number of aircraft (i.e. maximizing operational time, and possible revenue, for each aircraft). The model considers factors such as flight duration, energy consumption, and minimum turnaround time needed for charging and taxiing to find the optimal working solution. In this scenario, four electric aircraft were needed (MF001-MF004). Flights are depicted as diagonal lines between airports (y-axis), whereas stationary (turnaround) time is shown as horizontal lines.

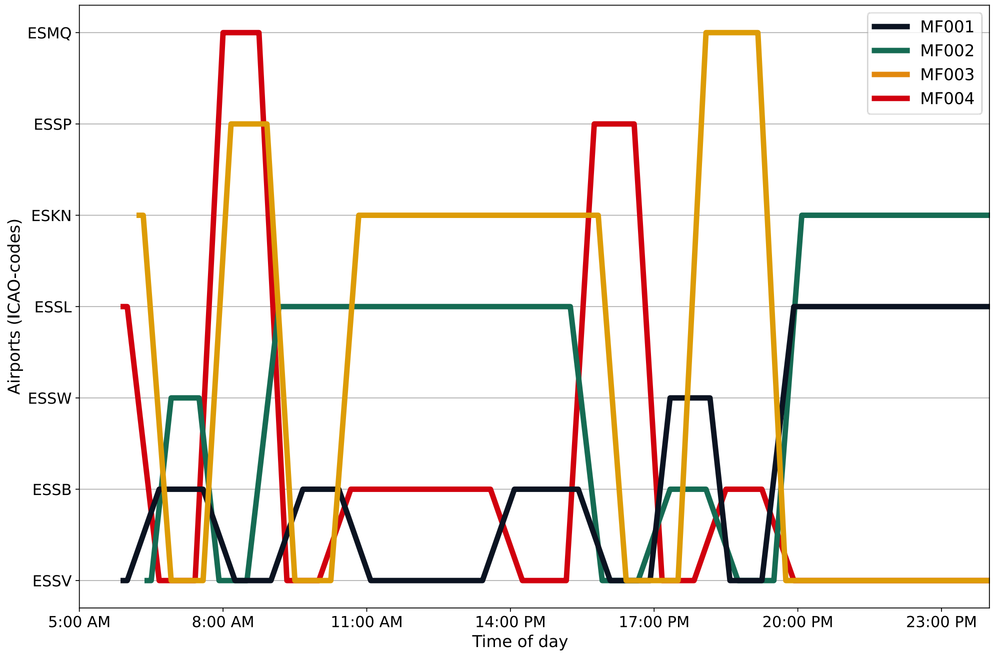

Figure 2: Visual representation of the optimized flight schedule. Flights are depicted as diagonal lines between airports (defined as airport codes on y-axis). Turnaroud times at airports are depicted as horizontal lines. Each colored line represent the daily traversal of one electric aircraft.

The schedule in Figure 2 is used to produce the charging scenarios at Visby Airport. Charging is simulated stepwise for each aircraft according to a maximum allowed charging profile, defined in earlier research [9] as,

$$P_{max}(t) = C_{rate}(t) \cdot E_b \tag{1}$$

$$C_{rate}(t) = f\big(SOC(t)\big) \tag{2}$$

where $C_{rate}(t)$ [1/h] is the rate at which the battery can be charged at time t, and E_b [kWh] is the total battery capacity of the aircraft. The value of $C_{rate}(t)$ is in turn a function of $SOC(t)$, which is the State-of-Charge (SoC) level of the battery at time t. For instance, a C-rate of 1.0C means that the battery can be charged from 0-100% in one hour.

Battery charging of EVs commonly follow a switch of modes, from initial constant-current, to constant-voltage (CC-CV), where the battery cell voltage determines which of the modes that is active. When maximum cell voltage is reached, the battery cannot utilize maximum charging power anymore. The battery cell voltage is in turn affected by the SoC. Besides electrical limitations, higher charging powers (or C-rates) lead to increased battery degradation. [11] Using the approach from earlier work by the authors [9], a maximum charging profile is modeled starting at 2.0C for a fully discharged battery and with a stepwise reduction until 0.5C. Thus, as the battery size is set to approximately 800 kWh in this study, the aircraft could charge with up to 1.6 MW each with a fully drained battery. Chargers with those power levels are not commercially available today, but there is an ongoing initiative for development of a Megawatt Charging System (MCS) standard [12].

2.2 Charging control strategies and power supply alternatives

2.2.1 Smart-charging

As stationary time availability and energy demand differ between aircraft, it might happen that utilizing the maximum allowed charging power is not necessary to recharge the battery fully before the next departure. On these occasions, the charging power could be reduced, delayed or redistributed strategically in time to balance the total load at the charging node (in this case, the airport). Based on this, a heuristic smart-charging algorithm developed in earlier research by the autors [9] is applied to the outcome of the reference charging case to explore what could be achieved regarding peak-power reduction and load balancing. The algorithm is given an objective to meet the energy demand of every aircraft, but where the aggregated load is kept below a specified target. For the work presented in this paper, the algorithm has been further developed, by altering the target load based on local photovoltaic (PV) electricity production, and/or by adding a battery energy storage system (BESS) to support peak power reduction.

2.2.2 Local electricity production to support charging

A simulation model is applied to estimate the potential contribution from local PV production. Since this is highly dependent on seasonal variations in solar irradiation and site-specific prerequisites like available land area or possible orientations, a scenario is specifically developed for Visby Airport.

Modelling of the PV installation is done using HelioScope, a web-based commercial PV system design software developed by Folsom Labs, providing accurate results for solar power production potential. In this paper, a feasible array location was selected as shown in Figure 3, where solar panels are installed as roofs on the airport parking lot. The array area is approximately 7,000 m^2 and constitutes 3,168 modules with a rated power of 370 W/module, thus totalling 1.17 MW installed power capacity. Solar irradiation data for the selected geographical location is extracted for 2021, and the simulation produces hourly yield throughout the year. Accounting for specified efficiency, tilt and azimuth angles, shading and conversion losses, the simulation results estimate an annual yield of 1.125 GWh (962 kWh/kWp).

Figure 3: Modeled PV array location (marked as blue sections) at Visby Airport used in scenario analyses.

Obtained PV production data is used to analyse the potential for reducing power import from the grid to meet the aircraft charging needs. This is done by altering the target load for the smart-charging algorithm, so that more power supply from the chargers is directed to times when power generation from the PV system is high.

2.2.3 Battery energy storage to support charging

Using a BESS is another potential solution to ensure power supply when needed, for instance by charging the BESS slower and/or during off-peak (when other loads are small) and discharge it when other loads are high (e.g. aircraft charging). This can also enable better utilization of local PV production which might not always match demand timewise, or if production is higher than the demand.

The developed simulation model functionality enable BESS to be added to the airport by specifying three main parameters; battery capacity (kWh) and maximum charging and discharging powers (kW).

The working principle of the BESS model is to prioritize peak shaving to meet the airport's target value. A gradient-based algorithm is introduced that goes through the differences between the required smart-charging power and the target value. For time steps where the smart-charging result exceeds the target, the BESS discharge, and conversely charges when the target exceeds the smart-charging demand. Based on this, the algorithm propose a charging/discharging pattern for the BESS as,

$$P_b(t) = P_m(t) - f_P \cdot \Delta P_{max} - P_s(t) \tag{3}$$

where $P_m(t)$ [kW] is the target power at time t, f_P is a value between [0,1] that dictates how much of the power difference the BESS should cover, ΔP_{max} [kW] is the maximum power difference between smart-charging and target, and $P_s(t)$ [kW] is the smart-charging power load at time t. If $f_P = 0$ is possible, the BESS will manage to perfectly match the smart-charging with target in that time step. However, the process is initiated by a value larger than 0 for every time step, followed by a simulation according to proposed charging/discharging pattern and control of two criteria:

1. That the BESS never exceeds maximum allowed charging or discharging power (as specified)
2. That SoC levels of the BESS manage to stay within a predefined window (20-80% used in this paper)

If both criteria are met, the value of f_P is halved, otherwise doubled, and the process is repeated until the problem converges.

3 Results

Four different scenarios are simulated and compared in terms of requirements and potential sources of power supply to meet the aircraft charging demand. The first scenario should be viewed as a worst-case, and the second scenario presents what can be achieved by introducing smart-charging (not optimized). The last two scenarios combine smart-charging with power supply from local PV generation, as well as using a BESS to cut remaining power peaks and more efficiently store produced PV electricity. Finally, an economic evaluation is conducted for a system including PV and BESS in terms of potential cost-savings for avoided peak power import or bought electricity from the grid.

3.1 Reference scenario

For the reference scenario, all aircraft charging sessions follow the maximum allowed charging profile in Equation (1). This reference case is denoted as *independent fast-charging*, as no 'smart' power management system is active. Rather all aircraft will charge according to their maximum charging profile until the battery is full (or until the next departure is due), without consideration to other charging sessions. Consequently, the aggregated capacity requirement for the airport becomes high. Next, the resulting load profile is obtained by summing the power load per time step for all charging sessions throughout the day at the airport. The peak-power requirement in the reference case became approximately 1.8 MW as indicated in Figure 4 (including losses between charger and aircraft battery). Three chargers were required to fulfil the demand with respect to the logistics for aircraft arrivals and departure times, though at most two charging sessions are active simultaneously. The maximum charger power was 900 kW, i.e. roughly 1C for the 800 kWh aircraft batteries, meaning that the aircraft batteries are not fully drained upon arrival (due to relatively short flight distances) according to the modeling approach explained in Section 2.1. Since no local electricity production or energy storage is applied in this scenario, the power supply is completely covered by the surrounding electricity grid.

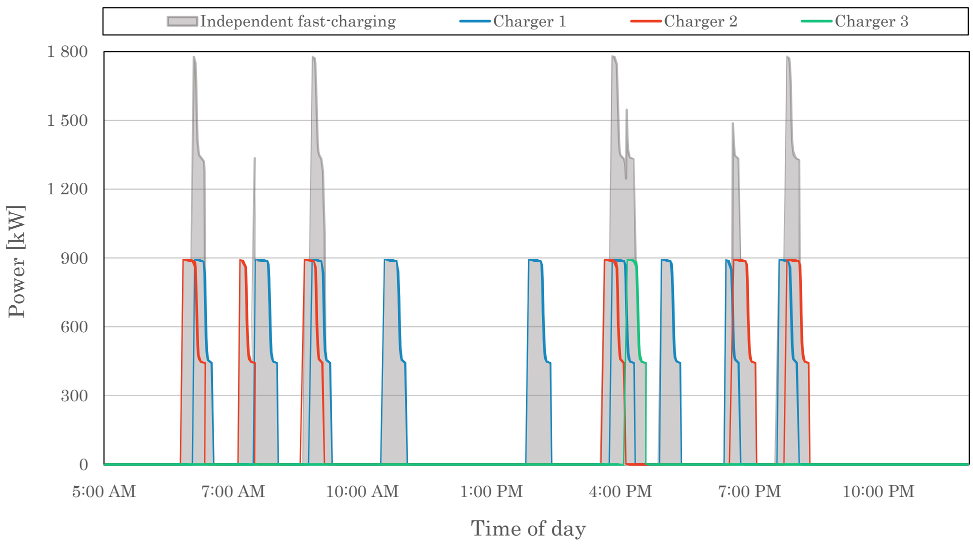

Figure 4: Reference scenario where all aircraft charge in accordance with the maximum allowed charging profile. Three individual chargers were needed. The load for all active charging sessions have been summed in each time step throughout the day to form the total load profile, denoted as independent fast-charging.

3.2 Smart-charging scenario

The resulting airport load after introducing the earlier described smart-charging algorithm is presented in Figure 5 compared to the reference scenario. The target for the smart-charging algorithm in this case is a flat curve covering the time steps from the first aircraft arrival until the last aircraft departure, calculated as,

$$P_{avg} = \frac{E_{tot}}{t_{tot}} \tag{4}$$

where E_{tot} [kWh] is the total energy demand, and t_{tot} is the total time from all aircraft visiting the airport throughout the day. As seen in Figure 5, this flat target curve could only be accomplished at the end of the day when the aircraft prepare to stay overnight, and thus can charge over a longer time period. There is still a visible peak pattern, though less tangible than the reference scenario, with a maximum peak at approximately 1.25 MW as seen during the morning hours in Figure 5. As no other source of power than the electricity grid is involved in this scenario either, the grid load will be same as the resulting smart-charging demand.

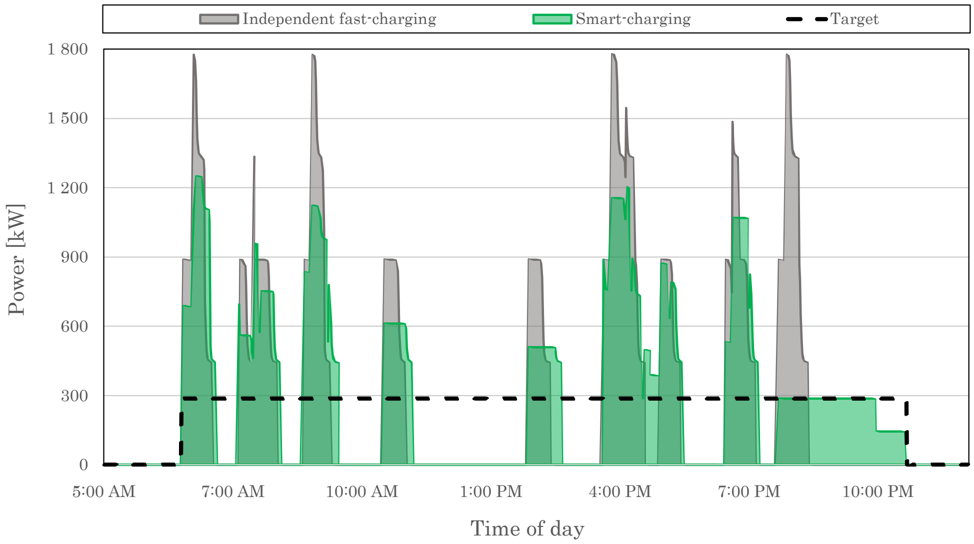

Figure 5: Difference from reference scenario load curve for aircraft charging after introducing the smart-charging algorithm. The smart-charging target is seen as a dotted line.

3.3 Smart-charging with PV scenario

To what extent locally produced PV electricity can improve the smart-charging result regarding the need for imported power is seasonal and intra-day dependent. Figure 6 shows variations for a selection of simulated days (summer day, winter day, spring day, autumn day) for the modelled PV array at Visby Airport. There is a mismatch between the PV generation and the aircraft charging loads, as PV generation tends to peak mid-day, whereas aircraft charging peaks during morning and afternoon hours; see Figure 5. The PV generation can deliver up to 900 kW for a clear-sky day. Still, this is significantly less in winter, offering a marginal contribution to load coverage.

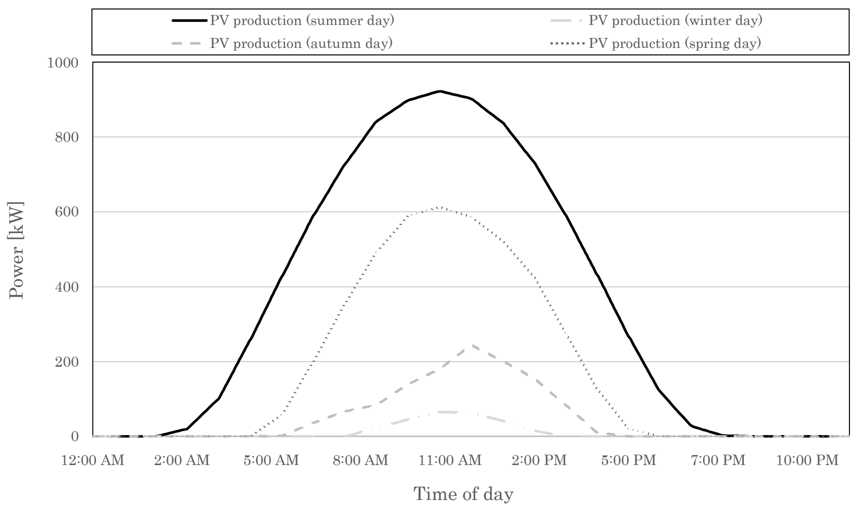

Figure 6: A selection of four seasonal days simulated with the PV model at Visby Airport. Summer day (2021-06-10), winter day (2021-01-01), autumn day (2021-10-15) and spring day (2021-03-22).

Throughout the continuation of this paper, analyses are based on *PV production (spring day)* according to the production curve in Figure 6. By feeding this into the smart-charging algorithm, its target power levels are changed, favouring charging at time steps with high PV generation, which means less power import from the grid. For time steps with little or no PV generation available, the target is instead decreased, aiming for a flat load curve.

As seen in Figure 7, the smart-charging algorithm now alters the power limitations of the chargers in time steps with PV generation. However, the PV plant's power supply is generally insufficient to fully satisfy the aircraft charging, especially in the afternoon and evening hours. Consequently, when subtracting the PV contribution from each time, several significant power peaks remain. Since other power sources have now been added that might decrease the demand for grid power, the resulting grid load will from now on be represented by negative values as seen in Figure 7.

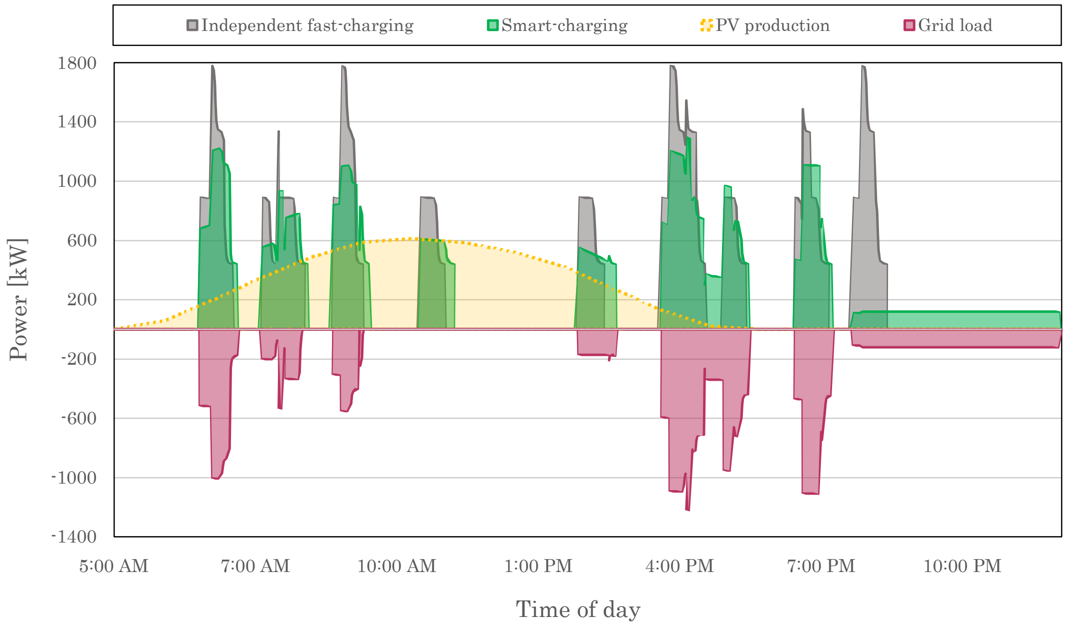

Figure 7: Difference from reference scenario load curve for aircraft charging and resulting grid load (negative) after introducing the smart-charging algorithm, and adding the "spring day" PV generation profile.

3.4 Smart-charging with PV & BESS scenario

The BESS model aims to eliminate the difference between smart-charging and the target load. If there is also a power supply from PV, the BESS will naturally act according to the PV-altered target load. Furthermore, the BESS will try to utilize the target power level to recharge whenever there is no or little need for aircraft charging. This also means that the BESS can charge more when PV generation is high, contributing to increased utilization of the locally produced electricity.

For this scenario, a BESS is introduced with 2 MWh total capacity and charging/discharging maximum powers of 2 MW (1C). However, it will not discharge with higher power than needed to match the smart-charging result with the target load, and not charge with higher power than the target allows.

Figure 8 shows the result when extending the earlier developed "Smart-charging with PV scenario" (Section 3.3) with the specified BESS. According to the earlier described working principle, the resulting charging/discharging pattern for the BESS has also been added here (positive when charging, negative when discharging). The resulting daily SoC of the BESS is shown in Figure 9. A starting SoC value of 50% has been set, which it manages to reach again at the end of the day. One thing to notice is that there is still unutilized mid-day PV generation since the BESS manage to charge fully (80%) before this, and then it is not needed until after lunch. In real life, other loads at the airport (heat, ventilation, lighting, service systems, ground support equipment, parked electric cars, etc.) might also benefit from the BESS, meaning it could make more use of locally produced electricity. Anyhow, left-over PV generation can also be a source of income by selling it to the grid. Using this system configuration, the resulting power import from the grid could be limited to roughly 200 kW.

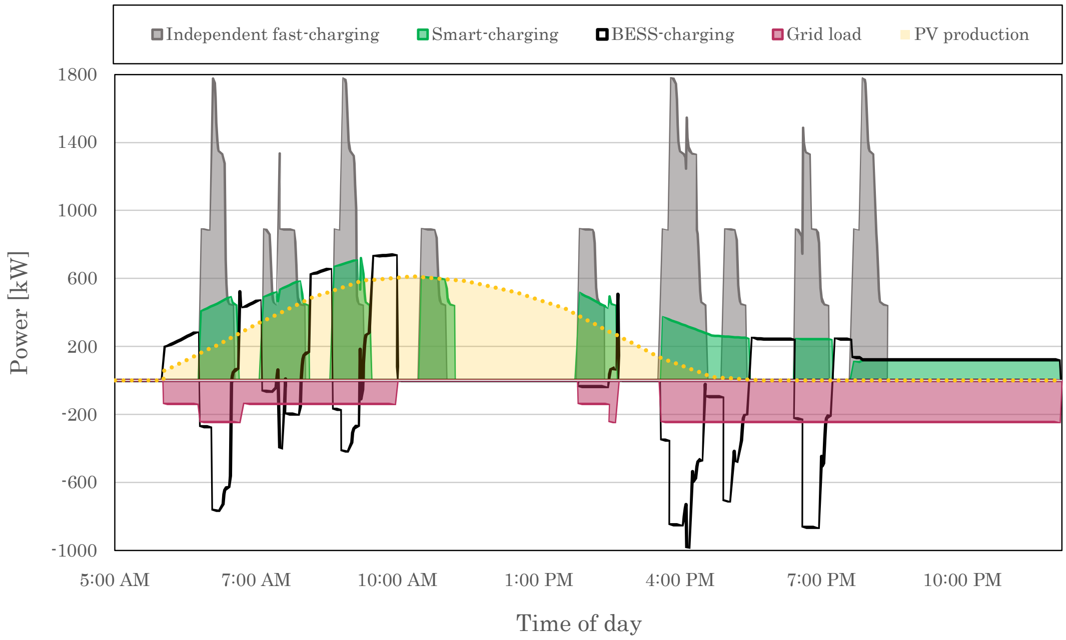

Figure 8: Difference from reference scenario load curve for aircraft charging and resulting grid load (negative) after introducing the smart-charging algorithm, adding the "spring day" PV generation profile, and introducing a BESS.

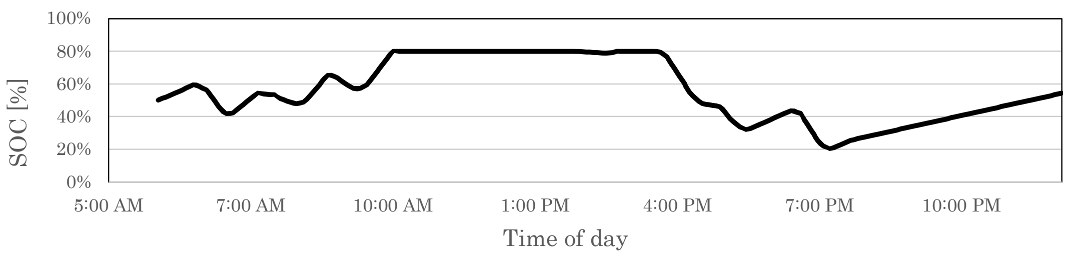

Figure 9: Daily State-of-Charge (SoC) variations for the BESS. The initial SoC is set to 50%.

3.5 Evaluation of economic feasibility for PV & BESS

An analysis of the economic feasibility of investing in a PV system and BESS is conducted based on potential savings due to the reduced need for peak power import, or amount of bought electricity, from the grid. Pricing models, including power tariffs, are under development. The customer is then charged based on both the amount of electricity consumed over time (kWh), as well as when it is consumed (kW). For instance, the customer might get charged based on the average of the N highest peak loads during the month.

Prices for PV systems have decreased rapidly over the last decade, and the blended average price in the U.S is currently estimated to be between $1.50-$2.00/W [13]. Costs for utility-scale lithium-ion battery systems (4-hour duration) are projected to decrease, but estimations for today are around $300-$350/kWh [14]. Using the lower end of the intervals, the proposed PV and BESS system would total at approximately $2.4M for a 1.17 MW PV plant and 2 MWh BESS.

Assuming that the highest montly peak power is equal to those observed in the aircraft charging scenarios, then smart-charging results in a 550 kW decrease in grid peak power import compared to the reference scenario, whilst adding PV and BESS leads to a 1550 kW decrease. For convenience, the airport is assumed to be charged monthly for the single highest peak. Further, adding PV and BESS resulted in approximately 50% less bought electricity from the grid (5500 kWh/day in the reference scenario, and 2800 kWh/day in the scenario with smart-charging, PV and BESS). The peak power tariff is varied between \$5-\$40/kW_{peak}, and the average electricity price is set to 11.27 U.S cents/kWh according to the average for commercial consumers in 2021 [15]. Seeing both "avoided" peak-power import and non-bought electricity as the cost-saving relative to the reference scenario, Figure 10 shows the computed pay-back period (PBP) in years for such a system purely based on these cost savings. Note that the results assume that every day of the year looks similar in terms of PV generation (spring profile) and utilization, which is not the case. Therefore, these calculations should preferably be performed throughout the year based on the simulated PV generation for each day, in future research.

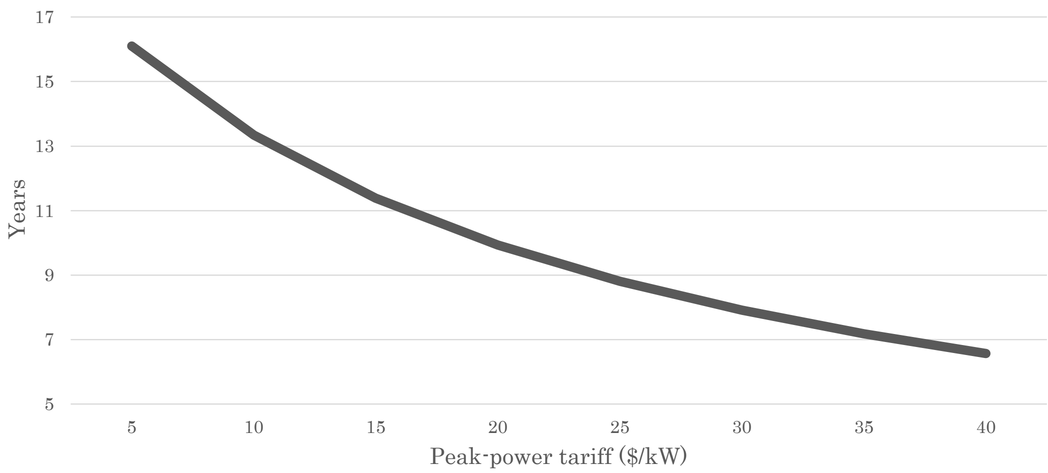

Figure 10: Estimated PBP in years of the PV plant and BESS as a function of peak-power tariff. The cost-saving per kWh for non-bought electricity import is estimated based on a set average for commercial customers in the U.S. 2021.

4 Conclusions

This paper explores smart methods and possible ways of solving the power supply puzzle at larger charging nodes where the requirements might become much more challenging. An airport was used as a case study, but the methodology is generic, meaning it could be applied to other nodes in continued research. Results indicate that there could be much to gain from using smart power management systems regarding reduced peak-power requirements and load balancing. Other than the cost perspective, the proposed solutions can offer other site-specific advantages. For instance, getting sufficient power supply infrastructure from the electricity grid ready in time to meet an accelerated adoption of electric transport might be more challenging in certain places. It is crucial to develop support by other means to these places, as they are also a part of a successful electrification in society.

The work presented is a start, but more research is needed to better understand future demand and possible solutions, in what situation a particular solution should be preferred, what the actual cost of these systems is and how that changes depending on site-specific prerequisites. Also, what new business models that could arise when these sites go from being a natural hub in the transport- and logistics chain, to becoming part of the local and regional energy system, should be investigated.

Lastly, the heuristic smart-charging algorithm presented in the work produces one possible solution for peak power reduction and load balancing, but not necessarily the optimal solution. Future work could focus on optimizing this, and in combination with local PV generation and BESS, as well as other active loads.

Acknowledgments

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Presenter Biography

Hampus Alfredsson (presenter) works as a researcher and project leader in electromobility at RISE Research Institutes of Sweden, Gothenburg. He received an MSc in Environmental Engineering and Energy Systems at Lund University in 2018. In his daily research, he works primarily with questions around charging infrastructure for electrified vehicles, including modeling and analyzing localization and smart utilization of the infrastructure from a fleet perspective.

Patrik Ollas is an industrial PhD student at RISE Research Institutes of Sweden in Borås, Sweden. He received his MSc in Mechanical Engineering in 2012 and is since 2017 pursuing his PhD degree in Electrical Power Engineering, focusing on solar photovoltaic, battery storage and direct current distribution in residential buildings.

Sara Ghaem Sigarchian works as a researcher and project leader in the field of energy systems at RISE Research Institutes of Sweden, Stockholm. She received a PhD in Sustainable Energy Technology from the KTH Royal Institute of Technology in 2018. In her daily research, she works primarily with questions related to local energy systems and positive energy districts focusing on techno-economic analysis, energy system modeling, optimization and multistakeholder engagement.

Christoffer Aalhuizen is a PhD student in electrical engineering at Uppsala University, focusing his research on high power charging for different types of transportation. In 2020 he received a M.Sc. Degree in energy systems and a B.A. in business and economics. He is currently involved in projects revolving how EV chargers supplying more than 900 kW can be implemented into power grids.

Jennifer Leijon is an associate senior lecturer working at Uppsala University, Sweden, currently with projects related to electromobility. She has a research interest in charging infrastructure and charging patterns for different types of electric vehicles, including electric aircraft. She received the Ph.D. degree in engineering physics in the Autumn 2020, from the Division of Electricity, and received her engineering physics degree in 2016.

Karin Thomas is an associate professor at Division of Electricity at Uppsala University. Karin received her PhD in engineering physics in 2008 and docent degree in engineering physics with specialization in renewable energy in 2020. She is currently involved in several research projects regarding charging of electric vehicles and currently the project leader of RES-Flyg.